European Technology Platform

Plants for the Future

Detailed Strategic Research Agenda 2025 and Action Plan 2007-2012

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Document layout
The Strategic Research Agenda is divided into three parts:

- Part one provides a brief and general overview of the **Plants for the Future** Technology Platform and its Strategic Research Agenda for a general readership, including policy-makers, non-specialist scientists, and interested members of the general public and other stakeholders. Part one contains a concise summary of the five challenges and how the Platform proposes to address them.
- Part two contains a detailed exposition of each of the five challenges. For each challenge, it covers an in-depth introduction to the issues pertaining to it, the goals the Platform plans to achieve, and deliverables and research activities for the next two decades. Owing to its length and technical nature, it is likely to be of primary interest to specialists in the particular field covered. However, all stakeholders are invited to read Part two or the sections of it that draw their attention. To ease the orientation of the reader each heading in part two has a reference number. C stands for Challenge, G stands for Goal, D for Deliverable and S for Scope. In this way [Ref.: C1.G3.D1. S2] after a heading indicate that the reader is currently reading scope three belonging to deliverable one, goal three, challenge one.
- Part three compiles the proposed activities for the period 2007-2012 as the 'Action Plan 2007-2012'.

This brochure contains part two and three, part one is a separate brochure. All parts are available at www.plantsforthefuture.eu

European Technology Platform
'Plants for the Future'

Strategic Research Agenda 2025

Detailed SRA

25th June 2007

Challenge one: Healthy, safe and sufficient food and feed

[Ref.: C1]

Plants and photosynthetic organisms are the Earth's life-support system. They are the primary source of energy, nutritional ingredients and tissue-building substances for most non-plant organisms. The unique process of photosynthesis results in the biomass needed by all living organisms. This means that plants are the heart of our food chain. Over the millennia, humans have strived through classical breeding to develop crops better suited to their needs.

Global demand for food and feed has been rising for decades. Food consumption expressed in kilocalories per capita per day has been steadily increasing worldwide. Between the mid-1960s and 1999, it increased globally by approximately 450 kcal/capita/day and by over 600 kcal/capita/day in developing countries. Similar trends are evident for protein availability.
Globally, the share of dietary energy supplied from cereals appears to have remained relatively stable over time, representing about 50% of dietary energy supply. Recently, especially in developing countries, the share of energy derived from cereals has fallen from 60% to 54% in a decade. In addition, the average worldwide supply of fat has rise by 21 grams/capita/day since 1967.

Food demand looks set to continue its upward trajectory. This will be fuelled by population growth – which is expected to reach 9 billion, from the current 6 billion, by 2050 – and improving living standards across the globe. For instance, meat production is projected to increase from 218 million tons per year in 1997 to 376 million tons annually by 2030. This will have a significant environmental impact, since, per hectare, animals generate less food energy than plants.

This implies that the worldwide demand for feed will increase dramatically as a result of the growing demand for high-value animal protein. Since Europe imports huge quantities of feedstock, either Europe will have to decrease its animal production or improve its domestic supply of feed by increasing its own feed output. Given the relatively low environmental and economic effectiveness of animal protein production, new markets look set to emerge for higher value-added food products from low-cost plant proteins.

In addition, it is now well established that feed and food are increasingly competing with non-food products (bio-energy and industrial products, such as bio-plastics for packaging) for acreage. Not only does this lead to a rise in raw material prices, but it also causes growers to abandon less profitable crops. One can already observe this development for certain minor crops which are essential to some food products but are no longer economically viable for the growers. Therefore, it is necessary to increase the yields of these minor crops to keep them competitive and maintain the diversity of available food raw materials.

All the above facts mean that more arable land will have to be farmed for feed and food or crop productivity will have to be boosted significantly.

As healthy as our diets
Conventional wisdom has it that people are what they eat. And, since prevention is better than cure, a healthy diet can often prevent the onset of some diseases and

health complications in later life. Poor diet and nutrition play a well-recognised role as determinants of major diseases including obesity, diabetes mellitus, cardiovascular disease, stroke, hypertension, and some types of cancer. Therefore, improved dietary practices could be central to preventive measures.

This means that, as Europeans continue to enjoy longer and more comfortable lives, the importance of balanced diets in terms of food composition, diversity, quality and safety will increase significantly over the next 20 years.

Accordingly, access to a wide variety of healthy and high-quality food is a must. It is a top public health priority to encourage people to eat healthier diets, as well as to exercise more and lead healthier lives. However, not everyone can and will switch to healthy alternatives. One way around this is to enhance the nutritional value of their diet.

Research will identify the advantageous and detrimental aspects of diet and plant genomics can help develop specially tailored food products.

Goals and deliverables

Research in this area should be geared towards the development of diverse, affordable, safe and high-quality plant raw materials for food products. It should also develop specialty food for specific consumer groups and needs. These will include improved food products with novel textures and tastes, better balanced and increased nutritional value, convenience, longer shelf life, etc.

It is also important to develop safe, high-quality feed that can be produced sustainably and in sufficient quantities. It should be free of toxic components that are harmful directly to animals, or indirectly to humans, or those that could damage the environment. Developing quality feed will not only be advantageous to the productivity, health and well-being of farmyard animals but it will also improve the quality of the meat.

Supply is another crucial issue. Livestock production in Europe currently consumes 160 million tonnes of feed, including that eating directly on grazing land, of which 90% is produced in Europe. As demand for meat continues to rise in the coming decades, plant research can help ensure a sufficient supply of feed by devising means of both boosting and stabilising yields and nutritional value.

Boosting output raises several environmental issues. In coordination with the other challenges of this document, especially challenge three on sustainable agriculture, future research in the field should look into the best ways of reducing the impact of new crop technologies, as well as that of current methods dependent on chemical fertilisers and pesticides.

The specific goals with deliverables that will be explored under this challenge are:

1. **Develop and produce sufficient, diversified and affordable high-quality plant raw materials for food products**
   - Diverse and affordable raw materials for food
   - Plant raw materials with improved composition in major storage compounds
   - Plant raw materials with improved characteristics for the production of nutritionally enhanced and more attractive food
   - Plant raw materials with improved composition for end product sensory characteristics
   - Plants with improved processing characteristics for food manufacture
2. **Produce, trace and control safe plant raw materials for feed and food**
   - Reduction of toxins and other harmful components
   - Plant raw materials which are less harmful to food
   - Traceability and control
3. **Tailor plant raw materials for certain health benefits and specific consumer groups**
   - Food for the prevention of chronic diseases – including obesity, diabetes mellitus, cardiovascular disease, stroke, hypertension
   - Reducing allergenicity/improving tolerance
   - Food for cancer prevention
4. **High-quality, sufficient affordable and sustainable feed**
   - Quality feed for quality food

Goal one: Develop and produce sufficient, diversified and affordable high-quality plant raw materials for food products

[Ref.: C1.G1]

Since top priority has traditionally gone to productivity and affordability, improving the quality of harvested plant products was not really an issue in the past. However, quality is an essential component of sustainable agriculture. This makes it necessary to increase our knowledge about the key factors affecting the composition and quality of proteins, oils and carbohydrates, secondary metabolites determining sensory characteristics, etc… Typical examples of this include the amino acid composition of proteins, the chain length and degree of saturation of fatty acids within plant oils, the polymerisation degree of oligosaccharides, as well as the composition in flavouring compounds. Each of these components can be optimised for different applications, such as plant raw materials with improved characteristics for the production of higher-quality food.

When considering these characteristics, it is important to keep the nature of the end product in mind. This means that the entire food-production chain, from fork to farm, has to be taken into account. For instance, the enrichment in one given chemical in the harvested plant raw material may be of no interest if it is lost during storage or processing. On the contrary, it may be of greater interest if it is a precursor of useful compounds formed during cooking or processing.

Food provides a context for social interactions and is also a pleasure in its own right. Consumers are showing increasing levels of discrimination between products based on their organoleptic and health properties. As long as they are affordable, food flavour and aroma are normally seen by the consumer as essential characteristics and often said to be the most decisive selection factor. In addition, social changes, fashion and food fads are triggering growing demand for processed or semi-processed foods and ingredients with a well-preserved original nutritional value.

Agricultural crops are important contributors to the flavour and aroma of processed foods. There are several ways in which plant science can address future demand in this area. First, this can be done by optimising the profile and possibly increasing the flavour, aroma and texture components of the raw material itself. A second opportunity lies in the better preservation of flavour and aroma during crop maturation, post-harvest treatment and storage. Third, the factors that play a major role in determining taste during processing should be at least maintained and possibly enhanced. This is because, in many cases, flavour and aroma derive from a combination of raw material and processing. Some crop modifications can contribute to these sensory improvements.

However, the above emphasis on quality and specific related characteristics of plants does not diminish the importance of yield which will drive the competitiveness of food crop production against that for non-feed/food products. Productivity is the only way to keep the growers committed to food/feed crops and to ensure sufficient supply at affordable prices. This is especially true for minor crops, such as durum wheat, herbs and spices, or even barley – all of which are key to maintaining food diversity.

Deliverable one: Diverse and affordable raw material for food

[Ref.: C1.G1.D1]

Whether it is for fresh produce or for processed foods, consumers expect diversity in terms of taste, nutrition, convenience and shelf life. This is leading to a kind of de-commoditisation of the supply chain of certain raw materials or ingredients which are already in the field dedicated to a given product category.

Therefore, it is important to maintain a high level of diversity for different crops, including those required for 'ethnic' foods. Minor species of vegetables, fruits, herbs and spices should also be characterised and their genetic diversity preserved. In many cases, this responsibility is currently left to some associations of private gardeners and is not discussed in an organized way at the EU level.

Efforts are required to characterise the nutritional and sensory diversity of crop species and their wild relatives. A thorough parallel genotyping and phenotyping is required with the objective being to identify genetic markers and genes associated with specific traits. This will permit the selection of genes and desirable characteristics.

An additional need is to understand the genetic and genomic consequences of environmental factors affecting plant quality. Such studies will reveal genetic and epigenetic mechanisms controlling plant plasticity in response to environmental stimuli and will lead to methodologies to improve plant performance and quality in different environments.

Time frame

Five years:

- Generation of a compendium of crop species and varieties required for maintaining food diversity.
- Creation of repositories for long-term storage of germplasm and current breeding work to maintain competitiveness of these species against non-food ones.

Ten years:

- Enhancing genotypes for agriculture and the transfer of beneficial characteristics to elite germplasm.

Twenty years:

- Genotypic and phenotypic (including metabolomic) mining of crop diversity for assisted breeding.

Deliverable two: Plant raw materials with improved

composition in major storage compounds [Ref.: C1.G1.D2]

Food derived from plants needs to be improved with respect to its general composition which may not be optimal. Plant proteins are generally poor in specific amino acids, such as lysine and methionine. Plant lipids often contain too high a proportion of saturated fatty acids. Starch composition of a product also has to be optimised depending on the planned utilisation. Furthermore, limitations in the quality of available food are also linked to the type of crops which can be grown in Europe – a problem which must be solved, if the EU is to achieve food autonomy.

Tackling the major quality issues for the main European crops requires a better understanding of the basic mechanisms governing the accumulation of major storage compounds. There are now many examples showing that major modifications of seed lipid or amino acid composition are antagonised by degradation processes safeguarding the global composition of the seed. A better understanding of the processes controlling the accumulation of stored compounds and this degradation processes is an important prerequisite for the improvement of the global composition of plant products.

Time frame

Five years:
- Analysis of regulatory pathways controlling the accumulation/degradation of storage compounds in different crops.
- Identification of steps needed to be modified for the improvement of global composition.

Ten years:
- Improvement of global composition through molecular breeding and/or transgenic approaches in different crops.

Twenty years:
- Production of new cultivars combining high yields and improved global composition and quality.

Deliverable three:
Plant raw materials with improved characteristics for the production of nutritionally enhanced and more attractive food [Ref.: C1.G1.D3]

Nutrients (such as vitamins and specific classes of unsaturated lipids), macromolecules (including fibres and anti-oxidants), mineral nutrients (such as iron or magnesium), and a variety of secondary metabolites are known, or at least presumed, to have an impact on the attractiveness of food and human health. For example, fruit production raises a number of specific issues as regards quality and taste improvement, often conflicting with shelf-life issues. This deliverable will target molecular breeding strategies to improve these different components of vegetables and fruits by pooling efforts on specific quality issues. Comparative genomics will help to improve different crops for similar objectives. This has to be done in close relationship with food consumers and processors in order to identify key targets.

Time frame

Five years:
- Analysis of pathways controlling the accumulation of specific metabolites/macromolecules contributing to the quality of different crops
- Identification of steps to be modified for the improvement of composition
- Identification of specific factors contributing to vegetable/fruit quality and taste
- Development of strategies for their improvement

Ten years:
- Improvement of composition and quality through molecular breeding and/or transgenic approaches in different crops

Twenty years:
- Production of new, high-quality and tasty varieties

Deliverable four:
Plant raw materials for food with increased and end product targeted sensory characteristics [Ref.:C1.G1.D4]

Sensory characteristics determined by the composition of the raw material are likely to become important quality criteria. The need for representative consumer panels is making this type of phenotyping very long and expensive. Genomics should, one day, allow researchers to identify key genes/pathways/metabolites linked to sensory performance. Information obtained can be applied to adjust available varieties to consumer preferences. This approach is even more challenging for complex aromas and flavours developed from precursors during processing (for example, chocolate) than for simple native ones (such as lemon). This approach can also be applied for colour and colour stability.

For instance, fresh tomatoes and tomatoes for processing are selected in part for their sensory characteristics. DNA markers of sensory traits have been identified by analysing the sensory profile of segregated populations in relation to their genetic background. These are now being used in breeding. The same type of approach is being pursued for red fruit varieties, such as strawberries. An even more efficient methodology would be to select on a genetic basis.

Another significant example is soy. It is an inexpensive and available protein source and can be used in many human or pet food products. Although popular in some parts of Asia, soymilk and derived products have not taken off in other countries for reasons of taste. Attempts have been made to get rid of the undesirable sensory characteristics, but they have so far proved unsuccessful. Plant science could help to identify the genes determining these undesired sensory traits and to modify them in order to achieve a more neutral taste. That would lead to greater consumer acceptance of this healthy product in Europe. Soy may also help satisfy growing worldwide protein demand by substituting some of the energy-inefficient meat consumption.

Time frame

Five years:
- Identification of the molecular components of plant raw materials influencing the sensory characteristics of food
- Analysis of the biochemical pathways leading to them as a basis for plant improvement. In this context, close co-operation with food specialists from industry is necessary

Ten years:
- Improving the quality of plants with regard to identified molecular components through molecular breeding, tilling and/or transgenic approaches in different crops

Twenty years:

- Production of new varieties adapted to fresh produce and food industry demands

Deliverable five: Plants with improved processing characteristics for food manufacture [Ref.:C1.G1.D5]

Plant raw materials play a very important role in processing performances (factory yield, energy consumption, etc.). For example, water solubility is helpful to all products being extracted and low hygroscopicity can help boost efficiency for all products that are dehydrated through spray drying, especially for all plant-based soluble beverages. However, the evaluation of these characteristics usually has to be carried out on a pilot scale that is often not compatible with the amounts of raw material available from ongoing breeding projects. Plant genomics/metabolomics can help to identify the key genes and metabolites determining the processability of raw materials and, thus, guide and facilitate the selection for processing characteristics.

• **Shelf life and packaging:**
Retailers and consumers could benefit from a longer shelf life for both fresh produce and processed food. In the case of processed food, consumers prefer 'natural' ingredients to additives which are often processed. Plant science could improve our understanding of oxidative processes occurring before, during and after processing, and develop raw materials that are less sensitive to degradation. This might be achieved by adjusting the fatty acid profile, modifying the oxidative enzymes, or even increasing endogenous anti-oxidant compounds. One example is potato for which storage, processing and derived products requires the use of additives that might be avoided with improved raw material. Not only additives but also specific and costly packaging systems, such as vacuum or inert gas in aluminium bags might be simplified. Benefits for the processor (cost), the consumer (shelf life after opening) and the environment may result.

• **Improved post-harvest characteristics:**
Some plant raw materials are still 'alive' after harvest. That may sometimes result in considerable changes in the quality and composition of the product during storage. Understanding the metabolic patterns that influence those changes and the genetic mechanisms underlying them may result in finding or developing varieties that have higher post-harvest stability and, hence, will result in foods with better flavour and aroma profiles. Such high stability of raw materials is also required to respond to the increasing demand for ever-lower levels of processing.

Time frame

Five years:

- In close co-operation with industry, identify the molecular components of plants that determine the post-harvest characteristics and shelf life of plant raw materials
- Analysis of the biochemical pathways leading to these compounds as a basis for plant improvement

Ten years:

- Improving the quality of plants with regard to identified molecular components through molecular breeding, tilling and/or transgenic approaches in different crops

Twenty years:

- Produce new varieties to satisfy consumer/processor demands

Goal two: Produce, trace and control safe plant raw materials for feed and food

[Ref.: C1.G2]

Crop and food safety is an issue upon which no European is willing to compromise. It is the key issue to consumer acceptance of any type of food. The long-term perspective (25 years) must be to achieve safety requirements for both fresh and processed foods. It should be made clear that food safety is not exclusively a GM issue, but also applies to organic and conventional crops.

All safety issues including the content of heavy metals or agrochemical residues have to be considered across the food supply chain. Less important are toxins and residues which will be destroyed or naturally eliminated during food preparation at home or in the factory. By contrast, undesired compounds formed during food preparation or storage must be controlled. All these food safety aspects have to be approached in a fully integrated 'fork to farm' approach – such an approach can clearly benefit from plant science research.

Similarly, the identification of compounds determining the harmfulness of certain raw materials could allow breeding for the absence of these compounds and move these species from non-food to food status, increasing the diversity of plant feed/food raw materials and the choices offered to consumers.

The following deliverables provide examples of areas where improvements can be made, but are by no means exhaustive.

Deliverable one: Reduction of toxins and other harmful components

[Ref.: C1.G2.D1]

A major goal is to produce feed and food which is free of components that are toxic for animals and humans. Such compounds can be of biotic origin, such as mycotoxins and anti-nutritional factors, or of abiotic origin, such as heavy metals or man-made xenobiotics (pesticides and other chemicals).

The comparison of the genomes of crop and model species belonging to the same botanical families has revealed a high degree of conservation in genome structure. This conserved synteny (genes occurring in the same order on the chromosomes of different species) will facilitate the transfer of information gained in model species to related crops and the identification of genes and quantitative trait loci (QTLs) that control resistance to diverse biotic stresses. Natural and induced genetic diversity will be exploited in breeding programmes to generate germplasm of plants resistant to biotic and abiotic stress.

Reduction of mycotoxins [Ref.: C1.G2.D1.S1]

Mycotoxins are secondary fungal metabolites which are toxic for animals and humans. These are natural contaminants and are some of the most poisonous toxins known in the animal kingdom. They are produced by fungal pathogens or epiphytes that multiply on plant materials in the field or after harvest. The most agriculturally important mycotoxins are aflatoxins, deoxynivalenol, nivalenol, T-2 toxin, zearalenone, ochratoxin, fumonisins, and patulin. Mycotoxins can also be metabolised by animals fed contaminated grains and passed into milk, eggs and other animal or dairy products entering the food chain. The occurrence of mycotoxins is sporadic and strongly dependent on agricultural practices (e.g., crop rotation and tillage) and climate, which means it cannot presently be predicted. Future changes in climate and the development of low-input agriculture (i.e. with reduced use of fungicides) will most likely increase their frequency. Many countries regulate for or suggest permitted levels of mycotoxins in feed and food due to their public health significance and commercial consequences. According to estimates by the UN's Food and Agriculture Organisation (FAO), world losses of foodstuffs due to mycotoxins are in the range of $1 billion (about €750 million) per year. In financial terms, the annual losses that mycotoxins incur for the feed and livestock industry in the USA and Canada alone are in the order of $5 billion (€3.75 billion).

Time frame

Five years:
- Develop high-throughput techniques for toxin quantification (biochemical tools and biological assays)
- Study genetic, molecular and cellular aspects of the plant-fungal interaction in order to decipher the mechanisms regulating toxin production and synthesis
- Identify novel resistance genes for the development of transgenic wheat and barley free of mycotoxins
- Develop more comprehensive safety data on dose thresholds for adverse effects of mycotoxins to improve risk assessment

Ten years:
- Map novel sources of resistance genes in germplasm and breed elite varieties accordingly
- Develop appropriate technology to rate contaminations of grain accurately

Fifteen years:
- Transform elite germplasm to demonstrate the efficacy of anti-fungi transgenes to provide increased protection against fungal infestation

Reduction of anti-nutritional factors and undesired compounds [Ref.: C1.G2.D1.S2]

Plants may contain compounds that can affect the growth, health, behaviour and biology of the animals and humans that consume them. These compounds can be analogues of nutrients and disturb their normal metabolism (e.g. L-DOPA and dicoumarol), inhibit digestive enzymes (trypsin inhibitors and anti-amylases), block nutrient uptake (lectins, phytates and tannins), and produce or generate during processing compounds that are toxic (gossypol and cyanogenic glucosides). A promising solution to this problem is to produce raw materials which do not contain these factors (for example, the over-expression of phytase can reduce the anti-nutritional effects of phytate and result in a more efficient utilisation of phosphorus and less residue in manure). The battery of genetic and genomic tools, including proteomic and metabolomic approaches, could be used to identify plant genes that control the synthesis of proteins or metabolites that have anti-nutritional effects. High throughput screening can be used to identify germplasm lacking the genes (or alleles) specifying the synthesis of anti-nutritional factors and breeding programmes can generate crops devoid of anti-nutritional factors.

Time frame

Five years:
- The variety of genetic and genomic tools, including proteomic and metabolomic approaches, could be used to identify plant genes that control the synthesis of proteins or metabolites that have anti-nutritional effects.
  - High throughput-screening can be used to identify germplasm lacking those genes (or alleles) which specify the synthesis of anti-nutritional factors and undesired compounds to be used later on in conventional breeding approaches.

Develop new food species by making some non food crops safer [Ref.: C1.G2.D1.S3]

Breeding for the absence of undesirable compounds would move species from non-food to food status and so would increase the diversity of plant food raw materials. An example of this approach is the one tried with lupins as a source of proteins for food and feed. More emphasis might be given to this kind of "turn around" strategy for consumers who may look for substitutes to certain raw materials for various reasons including nutritional and sensory ones.

Reduction of heavy metals [Ref.: C1.G2.D1.S4]

Heavy metals – such as mercury, cadmium, lead and copper – have occasionally been found in excessive quantities in food or feed, causing toxicity. Measures for quality control at critical steps of the food/feed production chain have been defined and the risk of contamination is now negligible. However, depending on the results of new toxicological studies, or for certain specific consumer categories, or as a precaution, the threshold of daily intake in foods might be decreased. Towards this end, studies should be carried out on heavy metal accumulation mechanisms in plant consumed organs and the genetic diversity for this characteristic in major and minor crops used in food products should be evaluated.

The situation for fish is quite different. The risk of high concentrations of heavy metals being present in fish is real. This has resulted in recommendations that people should not eat fish produced in fisheries and aquacultures too regularly. Heavy metals (as well as some xenobiotics, such as dioxins) can become concentrated in the ocean food chain, depending on the proximity of pollution sources, currents and climatic factors. The main feed for aquaculture is fishmeal which can contain relatively high concentrations of heavy metals and dioxins. Recent studies have shown that it is possible to replace fishmeal and fish oils with protein and oil-rich feedstuffs of plant or algal origin without affecting fish growth rates and taste. Research in fish nutrition and environmental sciences can define the best raw materials and the optimal proportion of plant-derived feed to allow a sustainable production of tasty and healthy fish. We can predict that, during the next decade, the use of plant-derived feed in marine and fresh water aquaculture will develop significantly, increasing the demand for protein-rich compounds.

Time frame

Ten years:
- Research in fish nutrition and environmental sciences can define the best raw materials and the optimal proportion of plant-derived feed to allow the production of tasty and healthy fish sustainably.

Reduction of xenobiotics [Ref.: C1.G2.D1.S5]

Plant protection chemicals (including insecticides, herbicides, fungicides and rodenticides) and their derivatives can accumulate in plant material and the agri-food chain in a variety of ways. The agrichemical industry and public-funded laboratories should pursue their search for biodegradable molecules acting at very low concentrations and having a low accumulation in the food chain, while studying their uptake, translocation and metabolism in plants. This should be done in close communication and collaboration with stakeholders representing different links in the food chain either through direct contacts or thanks to professional organizations, since some of the residues may be inactive until after processing, while others originally not harmful could become very toxic. Research efforts should aim to reduce the use of pesticides.

This includes the multidisciplinary investigation of the epidemiology of pathogens and pests, the mechanisms of plant biotic interactions, the influence of crop management (for example, crop rotations versus monocultures), the search for plant germplasms that are resistant to pests, and ways of decreasing the spread of epidemics. All these data should be integrated into modelling studies to define optimal practices to minimise the use of pesticides (e.g., through precision farming).

Major changes can be expected from the development of genomics and plant biotechnologies and their use in breeding programmes to grow plants which are resistant to pests and pathogens without chemical protection. The genetic and molecular dissection of resistance and defence mechanisms is progressing rapidly in model plants. Natural and induced genetic diversity will be exploited in breeding programmes to generate the germplasm of resistant plants. It is reasonable to expect that a major outcome of plant biotechnology and genomics during the coming two decades will be the construction of plants resistant or tolerant to the various pests and pathogens that threaten them.

Deliverable two: Plant raw materials which are less harmful to food [Ref.: C1.G2.D2]

Various compounds, such as plant inhibitors, may have a negative impact on the quality of food and feed derived from crops. Many of these plant compounds can be destroyed by simple procedures, such as

cooking. However, some are resistant to standard food preparation practices and need to be eliminated without compromising other aspects of crop physiology. Among these are compounds preventing digestibility, toxins (such as alkaloids or cyanogenic compounds), molecules with undesirable environmental effects (such as phytin), or simply compromising taste or smell. Molecular breeding approaches, tilling techniques and transgenics can all contribute to the improvement of crop quality by eliminating these deleterious factors. However, the real issue is the composition of consumed food and the bioavailability of these compounds. Therefore, they should be considered all along the food chain and during digestion.

One safety aspect may also be a result of a post-harvest metabolism forming undesirable components. For example, the sugar formation (hexose) during low temperature storage of potato tubers is negative from an organoleptic point of view, and also leads to the formation during cooking or frying of acrylamide – a highly undesirable chemical.

Time frame

Five years:

- Develop innovative analytic technologies for ant-nutritive, unfavourable organisms, biological or chemicals, which are systemic to or contaminating food plants
- Analysis of processes leading to and monitoring the accumulation of deleterious compounds
- Identification and implementation of steps to be modified for the improvement of new raw material composition and for minimising quality obstacles

Ten years:

- Improvement of quality by molecular breeding, tilling and/or transgenic approaches in different crops

Twenty years:

- Production of new varieties with no natural or process-derived deleterious compounds

Deliverable three: Traceability and control [Ref.: C1.G2.D3]

Current de-commoditisation trends do not always involve the vertical integration of food or retail companies. However, it certainly leads to better coordination of the supply chain which, in turn, improves traceability and control at each step of the food supply chain. The identification of markers for quality or sensory profiles will primarily be used to guide breeders, but it will also improve traceability and quality control up to the shelf. The identification of chemical, biochemical, DNA sequences or Near Infra Red profiles which might be used as quality markers should also be adapted and transferred for routine use in quality control procedures.

These markers will also enable the protection of intellectual property rights all along the chain, creating more incentives for downstream stakeholders to consider innovations in the upstream section of the agri-food chain. The development of markers for the control of the quality, identity and origin of plant raw materials delivered to the retail or food industry, either for fresh produce or processed foods is, therefore, highly desirable. Producing a good raw material is important. Being able to verify its nature and absence of adulteration is surely of equal importance.

Time frame

Ongoing activity through out the twenty years:

- When ever a new variety is developed as part of a breeding programme (as described in this SRA), in parallel it will be evaluated if a new marker has to be developed for this variety. If the conclusion is yes, this marker will be developed.

Goal three: Tailor plant raw materials for certain health benefits and specific consumer groups

[Ref.: C1.G3]

Conventional wisdom has it that a healthy diet can often prevent the onset of disease and health complications in later life. This carries health and financial benefits both for individuals and the public health system. Plant-derived foods can help combat obesity and diabetes, prevent indigestion, enhance mental alertness, improve bone and joint health, and reduce the risk of cardiovascular disease and cancer.

To achieve this requires enhancements to the composition of crop plants themselves or the use of more healthy compounds derived from plants. It is also important to make healthy food tastier by examining what properties attract people to certain types of food which are often unhealthy. In addition, it could be useful to develop products which prevent or reduce the uptake of unhealthy compounds found in other foodstuffs, such as fat.

Margarine is a good example of a food that helps support general good health. In the early 1960s, saturated fat was increasingly being replaced by unsaturated fat which cut up to 3% off the cholesterol content. The addition of phytosterol to margarine led to another 10% being knocked off. This significantly reduced the risk of suffering a heart attack for those who switched from butter to margarine. In fact, each 1% drop in cholesterol translates into a 2-3% reduction in the ten-year risk of coronary heart disease.

Genomic research will have a large impact on our knowledge of the relationship between food and health. Both national governments and the EU are investing heavily in nutrigenomic research which aims to map the human molecular response to various food components. This will eventually lead to a thorough insight into the effects of individual food components on human health and well-being. In addition, some scientists believe that this research field will enable the definition of genetic subgroups with specific dietary needs.

However, one important issue that will require regulation will concern the claims made about specific health benefits of products and appropriate labelling.

The consumer of 2025 might well be able to ascertain the specific health risks associated with his or her personal genetic make-up and to select a diet that diminishes them. It may then be possible to compose a well-balanced and personalised diet from a wide range of plant raw materials, both existing and tailor-made varieties. This necessitates a combined approach in which nutrigenomics experts co-operate with plant scientists and food technologists.

The following deliverables provide examples of areas where improvements can be foreseen, but are by no means exhaustive.

Deliverable one: Food for the prevention of chronic diseases – including obesity, diabetes mellitus, cardiovascular disease, stroke, hypertension

[Ref.: C1.G3.D1]

Almost half of the deaths caused by chronic diseases are actually attributable to cardiovascular diseases. Obesity and diabetes are also giving cause for concern, not only because they already affect a large proportion of the population, but also because they have started to appear earlier in life. Today, more than 8 million diabetics live in Germany. This number will rise to 10 million by 2010. Pre-diabetes, also known as syndrome X, is one of the fastest growing diseases among middle-aged people in western countries. It is estimated to affect a staggering 47 million Americans. As a final example, one in five US children is obese.

These ‘rich world’ diseases, as they are sometimes called, are spreading to developing countries as they modernise and industrialise. It has been projected that, by 2020, 75% of worldwide deaths due to stroke and 70% of deaths due to diabetes will occur in developing countries. According to the World Health Organisation (WHO), the number of people in the developing world with diabetes is set to more than double, from 84 million in 1995 to 228 million in 2025.

Low glycemic food [Ref.: C1.G3.D1.S1]

Low glycemic food, i.e. food containing carbohydrates which are slowly metabolised, will benefit middle-aged people with the propensity for developing metabolic syndrome or diabetes. Metabolic syndrome is a term used to describe a collection of pathologies which could lead to cardiovascular disease, type 2 diabetes and obesity. Offering a wide variety of such foods and communicating the benefits to the consumer will enhance the quality of life of affected individuals. There are several ways of lowering the glycemic index of food. Most products currently offering reduced glycemic response are technologically modified starchy foods. Increasing resistant starch content and reducing rapidly available sugars through biotechnological means could be a future alternative. Another approach to lower the portion of rapidly metabolised sugars is to replace absorbable amylopectin starch with inulin, oligofructose, beta-glucan or other more slowly digestible substitute carbohydrates from plants. A further approach could be the use of plant-derived products that reduce sugar uptake in the gut.

Time frame

Five years:

- Identify and characterise the molecular structures of plant-derived carbohydrates which determine metabolic rate in humans
- Analyse the biochemical pathways leading to these sugars as a basis for plant improvement

Ten years:

- Improve the quality of plants with regard to these sugars through molecular breeding, tilling and/or transgenic approaches in different crops

Twenty years:
- Produce new varieties for low-glycemic fresh or processed foods

Food enriched with vitamins, flavonoids, and carotenoids [Ref.: C1.G3.D1. S2]

There is considerable interest in the development of food products rich in vitamins, flavonoids, and carotenoids, because it is generally thought that they will be more beneficial to human health than dietary supplements. For example, tomato fruit and derived products are the principal dietary sources of lycopene and also contain large amounts of beta-carotene. Increased lycopene gives the fruit a more appealing colour, improves the quality of paste, and has proven nutritional value as an antioxidant.

Beta-carotene is the most potent precursor of vitamin A, deficiency in which can cause xerophthalmia, blindness, and premature death. Vitamin A deficiency is the most common dietary problem affecting children worldwide, and UNICEF, the United Nations children's fund, has estimated that improved vitamin A nutrition could prevent up to 2 million deaths annually among children aged between one and four years of age. Conversely, age-related macular degeneration (AMD) in the retina of the eye is the leading cause of severe visual impairment and blindness in the elderly. Increased consumption of non-vitamin A carotenoids zeaxanthin and lutein is associated with a higher macular pigment density. In addition to existing supplements or sources, the introduction of, or increase in, zeaxanthin and lutein in crops would make the food supply more versatile to help achieve higher plasma and tissue levels. Considering the increasing prevalence of AMD zeaxanthin and lutein could have enormous social and economic impact. Biotechnological approaches to elevate endogenous levels of zeaxanthin have been achieved in tomatoes and potato tubers.

Time frame

Five years:
- Transfer results in model plants to different crop plants

Fifteen years:
- Produce new varieties which satisfy a diversified market demand

Polyunsaturated fatty acids (PUFA's) [Ref.: C1.G3.D1.S3]

Long chain polyunsaturated fatty acids (PUFA's) are vital constituents of the human metabolism. For adults, eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) have physiological benefits, mainly in terms of cardiovascular protection, reduction of inflammation and mental performance. Infants benefit from the addition of DHA and arachidonic acid to infant formulae. Scientific evidence suggests that a prudent goal would be an intake of 0.5-1.0 g EPA and DHA per person per day. This means that the current intake should be increased three to fivefold, for which oils from plants may offer an affordable and sustainable supplement to the EPA and DHA currently extracted from fish, marine animals and marine micro-algae grown in bioreactors. Oil crops lack the genes to de-saturate and elongate their fatty acids to yield EPA and DHA. Nonetheless, the production of these specialty fatty acids in oil crops has been shown to be feasible with GM technologies and would constitute an interesting opportunity to make them cheaper and, hence, usable in a broader range of food products. Finally, the sustainability and the economics of modern crops might allow the incorporation of EPA and DHA into a wide range of foods.

Time frame

Five years:
- Identify all genes which are necessary to transfer PUFAs biosynthetic capacities from algae to higher plants

Ten years:
- Improve the quality of PUFAs in plants by using transgenic approaches in different oil crops

Twenty years:
- Develop GM varieties of oil crops which produce PUFAs

Deliverable two: Reducing allergenicity/improving tolerance [Ref.: C1.G3.D2]

An autoimmune disorder, such as celiac disease (CD), is triggered by the cereal protein gluten. In general, the quality of life of CD patients is severely affected. The disease in Europe and the Americas affects over 7 to 8 million people. The possible development of a genetic screening test for monitoring potential celiac disease could reveal an even greater number of people at risk.

At the present time, no drug has been developed to treat the disease, or even to minimise the symptoms. Therefore, a gluten-free diet is required but it is burdensome for the patients. Such an eating regimen brings severe limitations in terms of food palatability, remains difficult to source and is expensive compared to traditional food.

Providing gluten-free cereals generated by biotechnological means may be an approach that brings new benefits to patients. This would require changing the molecular structure of gliadin, the allergenic compound in gluten, or removing it altogether without losing sensory and technological performance characteristics of the cereal. However, the latter might be difficult as gluten is a structural component in wheat. Similar approaches may be suggested for other crops where allergy is a problem.

Time frame

Five years:
- Identify the plant genes for biosynthesis of gluten, especially gliadin. Analyse the underlying biochemical pathway as a basis for plant improvement

Ten years:
- Knock out or modify genes for the biosynthesis of gliadin in cereals by molecular breeding, tilling and/or transgenic approaches

Twenty years:
- Produce new varieties of cereals with non-allergenic gluten

Deliverable three: Food for cancer prevention [Ref.: C1.G3.D3]

There is increasing evidence that certain plant components play a role in reducing the incidence of cancer. Since the risk of cancer is partly age-related and the European population is greying, it is worthwhile investigating this feature of plantscarefully and in more detail. A major input will have to come from the etiology of the very diverse types of cancer, as well as from epidemiological studies. Once food ingredients have been identified to reduce the risk of a specific cancer, agriculture and food industry can provide for the active ingredients to individuals at risk.

Food products with anti-tumoral properties [Ref.: C1.G3.D3.S1]

Work will have to focus on specific types of cancer and on defining whether there is a genetic predisposition among certain population groups. Input from plant science will lead to an understanding of which components play a role in cancer prevention and how these are produced by the plant. Based on that broader understanding, research will help develop plant products enriched in special compounds. However, regulatory issues in this area still need to be addressed.

Time frame

Five years:
- Identify plant ingredients which reduce the incidence of cancer

Ten years:
- Analyse the underlying biochemical pathways in plants as a basis for improvement.
- When required, identify and characterise plant genes which code for ingredients with preventive properties

Fifteen years:
- Improve plants with regard to active metabolites through molecular breeding, tilling and/or transgenic approaches in different crops

Twenty-five years:
- Produce new varieties with improved metabolite composition

Goal four: High-quality, sufficient, affordable and sustainable feed

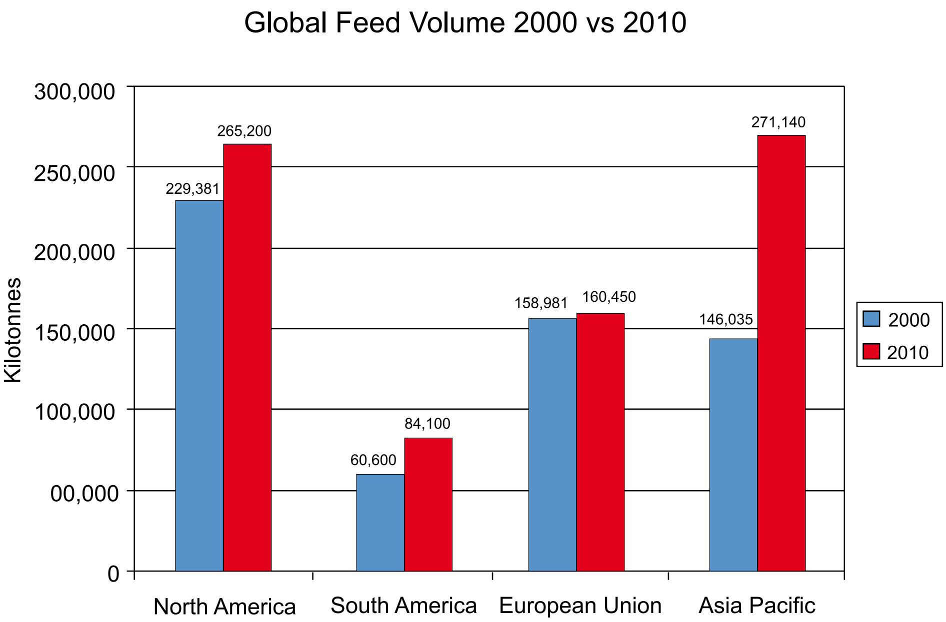
[Ref.: C1.G4]

Over the past two decades, global meat production has increased rapidly, especially in developing countries where rising incomes have led food demand to shift from cereals to meat and dairy products. In the EU and other developed countries, the trend in animal husbandry is moving towards healthier, more convenient and varied meat and dairy products. To meet burgeoning global demand for meat, the livestock sector is rapidly industrialising to tap into the associated economies of scale. At the same time, environmental concerns in the developed world – in particular in the EU – may push agriculture to more sparsely populated areas and less developed countries with lower environmental standards. Finally, the same concerns apply to feed as to food when it comes to the increased competition for arable land for other non-food/feed uses.

Faced with the conflict between rising demand, environmental concerns and increased land competition, the application of new agricultural technologies can help provide a more sustainable solution. Advances in plant breeding methods could help boost crop yields and quality (palatability and digestibility), while reducing costs. These new technologies will enable European farmers to be competitive in the global feed market.

Industrial feed consumption for livestock production in the EU-15 was largely stable over the past years. While global feed production is set to increase, EU-15 production levels are expected to remain constant (Fig. 1). The Union imports about 40 million tons of grain each year – 70% of these protein-rich compounds are used for feed. In the future, the EU will most probably continue to be a net importer of feed for livestock production. This is because important feed ingredients cannot be grown in sufficient quantities in the Union. Though expecting a steady growth in crop yields, Europe is unlikely to help meet growth in the worldwide feed market without important improvements in plant and crop sciences.

Today, scientific effort is mainly focused on input and output traits in the major American crops: soybeans and maize. These crops are of limited importance in Europe and most of the developing world. Therefore, European leadership must be reached by extending the efforts to other feed crops which are more important in Europe and Asia, e.g. wheat and rapeseed, or new ones, such as lupins.



Source: European Feed Manufacturers' Federation (FEFAC) and the European Commission

Deliverable one: Quality feed for quality food

[Ref.: C1.G4.D1]

Improving the quality of feed increases the efficiency of assimilation of the various nutrients for optimal productivity and minimal environmental impact, and enhances the quality of animal products for human nutrition. Studies in animal nutrition and physiology are defining the targets – that is the optimal composition of feed in macro- and micro-nutrients – to ensure maximum palatability and digestibility.

Plant raw materials with optimised concentration, quality and composition of macronutrients [Ref.: C1.G4.D1.S1]

Macronutrients are proteins, carbohydrates and lipids, with cereals as the main source of carbohydrates, and oilseed crops as sources of lipids and proteins, respectively. Improved protein, carbohydrate and oil content will be crucial in order to meet increasing global demand, since the supply of arable land is limited. Corn and wheat as the main source of feed starch could be a target for altering seed metabolism towards starch accumulation, whereas different crops could help improve oil production. Not only macronutrient quantity but also macronutrient quality is of considerable importance, because an optimised composition of the different macronutrients will result in more economical livestock production. For example, optimising the amino acid composition of soybean and rapeseed proteins used in livestock production will reduce the requirement for feed additives, such as lysine and methionine.

Time frame

Five years:
- In close collaboration with agronomists and nutritionists, assess the macronutrient characteristics needed within a plant
- Identify germplasm and genes that are important for the trait and introduce them into breeding programmes

Ten years:
- Perform a large-scale analysis of the diversity of the macronutrient composition phenotypes in existing collections of crops, in related species and in other plant species
- Develop understanding of the cellular and molecular basis of the composition of macronutrients in model species and major crops; carbon and nitrogen partition between sources and sinks; mechanism of accumulation of proteins, carbohydrates and lipids in the seeds for grain products and shoots and leaves for forages

Fifteen years:
- Identify genotypes in classical or novel crops with improved macronutrients and identify quantitative trait loci (QTL) and introduce them into breeding programmes

Plant raw materials with optimised concentrations of micronutrients [Ref.: C1.G4.D1.S2]

Micronutrients in raw materials include vitamins, minerals and functional components. Similar approaches as those described above for macronutrients should be followed.

Time frame

Five years:
- In close collaboration with agronomists and nutritionists, assess the micronutrient characteristics needed within a plant
- Identify germplasm and genes that are important for the trait and introduce them into breeding programmes
- Analyse the environmental effects and agricultural practices on micronutrient composition for major crops in Europe

Ten years:
- Develop an understanding of the cellular and molecular basis of the composition of micronutrients in model plants and major crops
- Identify germplasm with improved micronutrients and identify relevant genes and introduce them into breeding programmes

Plant raw materials with improved palatability/digestibility [Ref.: C1.G4.D1.S3]

Some compounds are known to improve palatability; others have the opposite effect. Palatability and digestibility are very important characteristics that help ensure the best use of feed in terms of nutritional efficiency and environmental protection. The development of assays for determining the palatability of various feed components at a mass scale, without requiring the involvement of large animal populations, is needed. For increasing digestibility, there is a need for interdisciplinary research bringing together plant breeders, plant technologists and animal nutritionists:

Time frame

Five years:
- Phenotype major feed crops (grains and forages) with regard to palatability/digestibility

Ten years:
- Link phenotype to molecular basis

Fifteen years:
- Identify improved genotypes/QTLs/relevant genes and introduce them into breeding programmes for developing new varieties which are richer in desired palatable compounds and poorer in undesired ones

Challenge two: Plant-based products – chemicals and energy

[Ref.: C2]

The development of the knowledge-based bio-economy – involving a global industrial system based on renewable plant-derived products as an alternative to the current fossil fuel-based system – constitutes by far the most challenging and promising opportunity in terms of economic, environmental and societal potential. Until recently, this concept of a bio-based industry was perceived as a desirable development in the distant future because there were no strong economic drivers to support its development. However, three recent developments have provided the necessary stimulation. First is the sharp rise in crude oil price since 2004. Second is the rapidly growing consensus that the root causes of climate change need to be addressed seriously and urgently. Third is the fact that end users are looking to the development of innovative new raw materials. Thus, the concept of a bio-based industry is rapidly becoming reality through a combination of technology push and market pull. This transition is receiving strong support from policy-makers and a global financial community that is investing billions in novel industrial initiatives, both in developed and developing countries.

The transition from our current fossil fuel-based industries to bio-based industries will have far reaching and immense effects on agriculture, industry and society. Most importantly, the transition will require considerable investments in research into feedstock production, conversion processes and large-scale capital infrastructure. In essence, it is envisaged that agricultural raw materials will become feedstocks for the production of biochemicals, bio-energy and biofuels.
In addition to the contribution of forestry to bioenergy, these basically constitute novel applications of agricultural production, requiring appropriately designed crop species different to those that are currently used for food and feed production. The immense challenge of the bio-based industry will be to develop economically competitive and environmentally compatible novel crop and production systems that will gradually replace the current fossil fuel-based industrial production of materials and energy. To meet this challenge we will need policies to support the sustainable growth and development of bio-based industry across the European Union and globally. In particular, policy decisions will have to be taken in relation to competing demands for land use from food and feed production to non-food products including biofuels. Reform of the Common Agricultural Policy (CAP), in which market forces will increasingly determine which crops are grown across Europe, will have to address these issues.

The deployment of these novel non-food crop species on a scale of tens of millions of hectares in the coming decades undoubtedly constitutes the biggest challenge in agricultural history. The deployment will also require private investments in the order of several billions of Euros. However, the current stringent regulations governing genetically modified crops in Europe represents the most important barrier for private investment in plant biotechnology. If this barrier is not mitigated, the deployment, for example, of high efficiency energy crops in Europe will be seriously threatened, with the consequence that Europe may become dependent once more on imports to meet the targets set out in the EU's Biofuels Directive.

Policy measures are urgently needed to create an environment that is fully conducive to private investment in plant biotechnology. One such policy measure is an implementation of the GM regulatory framework specifically tailored for genetically modified non-food crops that would create a strong incentive for investment in R&D in all plant-based applications, particularly biofuels. Today, the lead market for biofuels is primarily supported by tax incentives and other forms of government subsidies, but these measures are not sustainable in the long term. Biofuel production in Europe can be cost competitive on the international market provided that high-tech energy crops, adapted to the different climatic regions and optimised for sustainable biomass yield under low input agriculture can be realised. The novel implementation of the European regulation for genetically modified non-food crops not only constitutes a condition sine qua non for the development of European energy crops, but would also mitigate in part the negative consequences for private investment resulting from the current GM regulations on food crops. It is imperative that these biotechnologies can be used to ensure a competitive position for Europe in the new bio-economy – without these advances the European position in both agriculture and industry will increasingly fall behind other countries in the global marketplace.

A clear vision is urgently required for the research and development activities needed to underpin and optimise the use of plant-based renewable resources. This vision cannot be set in stone, since it is impossible to anticipate the immense technological developments in this field in the coming decades. However, it is essential that the multi-functionality of crops is addressed to optimise the future use of agricultural raw materials in the bio-refineries which will produce a range of products and fuels. This challenge must be updated regularly to capture new developments and innovations.

The specific goals with deliverables that will be explored under this challenge are:

1. Biochemical production
- Pharmaceuticals
- Specialty chemicals and enzymes
- Plant-derived oils as industrial feedstock
- Polymers
- Fibres

2. Bio-energy production
- Production of biomass
- Conversion of biomass
- Innovative concepts for whole plant utilisation

3. Enabling research for plant based products
- Development of production platform crops and extraction processes
- Systems for plant production

In practical terms, these goals are fully integrated and contribute to a bio-manufacturing base involving integrated bio-refineries. For clarity in the present document, topics within each are described separately. The topics represent realistic goals that can be achieved by building on European expertise.

Goal one: Biochemical production

[Ref.: C2.G1]

We already obtain bulk materials from plants in the form of wood, carbohydrates, oil, fibre and protein. These make up about 5% of our industrial raw material needs. The remainder comes mainly from fossil fuels, such as petroleum and natural gas. It is a clear objective of the European Union to increase the percentage of plant derived renewable resources used for synthesis of chemicals and materials. Indeed, plant-based resources can certainly provide far more functionalities for society and industry than at present. These may relate to commodity-scale products, as well as to new uses for materials and molecular components, whether in native form or following post-harvest modifications. New plant raw materials may include medicines, speciality chemicals and enzymes, industrial feedstocks, polymers and fibres, produced either from conventional or genetically modified plants. These materials will have applications in the health, nutrition and materials industries.

Strategies for the replacement of fossil fuels will come about gradually. An ambitious but eminently achievable goal is to explore the uses of new plant raw materials with better performing features and to develop plants as "green factories" for the production of new compounds. The benefits of these developments may range from cheaper, safer or more environmentally friendly production methods to the development of new and improved products for the consumer.

At present, it may only be possible to predict in the broadest terms, the types of business fields that might emerge, the types of biological know-how that will be required for success, and the nature and identity of the first 'pioneer' products. At this stage then, it is important to encourage technology platforms that embrace current potential advances and that are enabling for a multitude of applications, rather than exclusive and selective for applications perceived at this point in time to be worth pursuing.

In this section, we describe the capabilities of plants as green factories for the production of five significant groups of green products. For most of the first anticipated products, the important genes and metabolic pathways are already identified. This information will allow the development of strategies for boosting production in plants. The products have been divided into five deliverables.

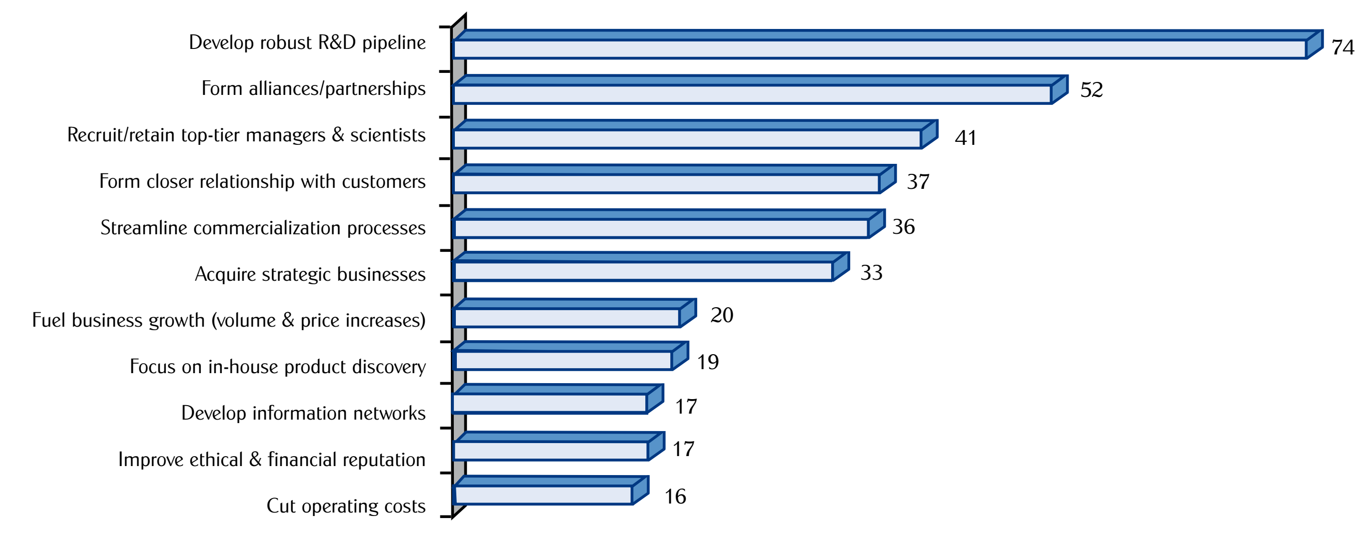
Deliverable one: Pharmaceuticals

[Ref.: C2.G1.D1]

Plants have historically been and always

Which of the following strategies are most important in securing your company's succes through 2015?

Source: Copyright © 2006 Deloitte Development LLC. All rights reserved. (% survey respondents)



will be an important source of pharmaceutical products. Currently, about two-thirds of all antimicrobials and half of all anticancer drugs are directly or indirectly derived from natural resources. Our dependence on natural plant-derived products is clear, but the recent concept of plants as green factories provides the basis for groundbreaking new possibilities in medicine.

The prevention and treatment of infectious disease is one of the most compelling challenges facing the rapidly expanding world population. Infectious disease is the main cause of death in the world, and healthcare is generally recognised as key to overcoming global poverty, as well as lightening the disease burden in both developing and developed countries. Amongst the key factors for progress will be our ability to identify new medicines, test and produce these in a cost-effective manner and in adequate quantities.

Plants are set to become a valuable resource in the production of pharmaceuticals in two major ways: as a source of recombinant protein medicines and as a source of natural products. In both cases, the principal advantages of plant-based production systems are flexibility, scalability and cost.

Plants are remarkably flexible in the range of complex proteins and metabolites that they produce and can be engineered to manufacture. Production of these medicinal compounds in plants would be scalable to an agricultural level, where virtually unlimited numbers of plants can be grown to produce the desired product. No other production system offers the potential scalability of plants. The cost advantage emerges partly from economy of scale but mainly because the cultivation of plants is essentially low-tech and inexpensive. A detailed cost analysis of a plant production system for a recombinant vaccine for example, is available at http://www.biodesign.asu.edu/centers/idv/projects/provacs

A source of recombinant protein medicines

[Ref.: C2.G1.D1.S1]

The use of plants to produce pharmaceuticals was a concept first proposed in the 1980s, and substantial progress in developing proof of concept has already been achieved, culminating in a number of clinical trials. One of the main motivations has been to control the spread of infectious disease. For example, vaccines are the most efficient and cost-effective means of controlling and eradicating disease, but most vaccines cannot be made in sufficient quantities to make a global vaccination programme possible. Indeed, 30 million children per year are inadequately immunised against the six major vaccine-preventable infectious diseases: tuberculosis, polio, measles, tetanus, diphtheria and pertussis.

The production of recombinant pharmaceuticals in plants can potentially address many of the difficulties and challenges posed by existing methods of production. The potential combination of low cost coupled with highly scalable manufacturing capability is particularly important for many pharmaceutical products, particularly when it comes to developing countries.

It will also enable the development of new applications that are currently not achievable with fermentor-based technologies, such as passive immunotherapy with monoclonal antibodies and topical anti-infectives.

The application areas that can benefit most from a plant-derived production system are:

1. Medicines that are required in very large quantities, such as sub-unit vaccines, monoclonal antibodies, HIV protein microbicides.
2. Medical indications that require proteins that can only be made in plants, such as secretory IgA antibodies. At present, this major class of antibody, which is important for the prevention of infection on mucosal surfaces, cannot be made efficiently by any other means.
3. Medicines that are specifically designed for production in plants, such as recombinant immune complexes. Our growing understanding of protein production in plants has led to the ability to engineer molecules with enhanced immunological properties.

Vaccines: Plant systems can be used for the production of sub-unit vaccines and these can be formulated either as injected vaccines using highly purified preparations or as orally administered vaccines using partly processed plant material.

A plant-derived vaccine has the potential to be superior to other methods of production in several ways. It significantly reduces manufacturing cost and enables a scale of production that would facilitate global access. It would also enjoy a level of heat stability that would permit storage under ambient conditions without refrigeration. Oral delivery would be possible using partially processed plant material.

Antibodies: Monoclonal antibodies represent the most important group of pharmaceutical biologics, accounting for more than 20% of all the biopharmaceuticals under current development. Their specificity for particular antigens allows them to be used as diagnostic agents, therapeutic drugs and even as new industrial enzymes. An estimated 1 000 therapeutic antibodies are being developed by biopharmaceutical companies around the world. Over 200 antibodies are already in clinical trials and it is likely that many monoclonal antibodies (such as Herceptin) will prove to be blockbuster drugs.

Currently, most antibodies are produced in Chinese Hamster Ovary cell lines. However, such expression systems are expensive to establish, maintain and scale up, and the potential for contamination with adventitious agents, such as prions or oncogenic DNA sequences is a constant concern. Plants represent an efficient alternative for the production of recombinant antibodies. Research over the last ten years has shown that plants can produce a variety of functional antibodies and the first plant-produced therapeutic antibodies have already reached clinical trials. Given the scalability and up-front economic benefits of this production system, we are likely to see many more recombinant antibodies produced in this manner in the future.

Other prophylactic or therapeutic proteins: There are many other examples of prophylactic or therapeutic proteins that fit the three criteria outlined above. Some are likely to reach the clinic within the next couple of years, such as human serum albumin and aprotinin, whilst others are at an earlier state of development, such as the protein HIV microbicides.

Time frame

Five years:

- The manufacture of products from genetically modified plants and entry into human clinical trials (based on good manufacturing practice)
- Science-based systems for the risk management of GM pharmaceutical production in plants
- First generation regulatory pathways for products derived from genetically modified plants
- Re-evaluation, diversification and expansion of major diseases targeted by European funding agencies, and increasing collaborative initiatives with health research agencies in developing countries
- Definition of new disease targets and commercially viable pharmaceuticals to be produced in plants
- New technologies for optimising expression and accumulation of recombinant proteins in plants
- Development of new plant-based production strategies

Ten years:

- Improved commercial recombinant pharmaceutical products from plants
- Biotechnology-based systems for providing quality assurance and quality control
- Evolution of regulatory standards for plant-derived pharmaceuticals based on previous European and international experience
- Application and transfer of European knowledge base to developing countries for humanitarian purposes

Twenty-five years:

- Development of molecular engineering strategies to optimise the metabolic responses to genetic modification
- Established pipeline for pre-clinical and clinical development of commercial products

A source of natural products – secondary metabolites [Ref.: C2.G1.D1.S2]

The importance of plants as a source of new drug molecules is illustrated by the fact that, in the past 20 years, 28% of new drug entities were either natural products or derived from them as semi-synthetic derivatives. Prescription drugs containing phytochemicals were valued, in 2002, at over $30 billion (about €23 billion) in the United States alone. The majority of pharmaceutical plant secondary metabolites are still isolated from wild or cultivated plant species. However, many of these plants are difficult to grow or are becoming endangered due to over-harvesting.

Moreover, 24% of drugs were synthesised after the molecule was first discovered from natural sources and the use of plant secondary metabolites as lead structures for chemical synthesis will be an important development path. The chemical diversity of plant compounds undoubtedly serves as an inspiration which cannot be provided by libraries consisting solely of synthetic entities. Furthermore, new techniques should ultimately allow an even greater semi-natural diversification towards the improved lead compounds so much needed by the pharmaceutical industry.

Secondary metabolites comprise a vast diversity of different chemical classes produced by plants for use in human and animal health, from anti-oxidant to anti-cancer compounds. There are already many examples of natural plant pharmaceuticals in which secondary metabolites act as anti-microbials, anti-hypertensives, anti-inflammatories, as well as primary cancer therapeutics.

In addition to the currently known secondary metabolites, plant cells can be utilised for discovery of totally new compounds (including carbohydrates, lipids, peptides or proteins) to add value to chemical diversity of the whole plants. The compounds could potentially be used both by the pharma and non-pharma industries. Only about 10% of the existing 400 000 higher plant species have been characterised chemically, so the chemical diversity of the plant kingdom represents an immense untapped reservoir of molecules with potential pharmacological value. Functional genomics and metabolite profiling offer unprecedented possibilities to explore the extraordinary complexity of plant biochemical capacity. New genomics tools can be used to engineer the production of known target metabolites or to synthesise entire novel compounds by combinatorial biochemistry in cultivated plant cells.

There are four key areas in which research should focus in order to realise fully the economic potential and utility of plant secondary metabolites:

1. Analytical and screening methods to explore chemical diversity rapidly and at low cost: the range of secondary metabolites in any given plant species is highly influenced by internal developmental cues and external environmental challenges. There are clear examples of bioactives restricted to a specialised group of differentiated cells – such as in subcompartments of glandular trichomes – located on specific organs at only certain stages of development; in order to explore fully the potential existence and utility of secondary metabolites, new rapid, cheap and easy-to-use methods for analysis of chemotypes in small quantities of tissues/extracts must be developed; unless the chemical diversity can be efficiently and rapidly analysed, identification of defined natural products, together with an awareness of their sites of synthesis in the plant, will not be possible.
2. Linking defined novel and natural chemicals to functionalities: new extraction and separation methods must be designed to maintain potential biofunctionality of the plant metabolites, while ensuring effective purification of individual compounds that can be assayed for utility. Decoration of natural product scaffolds in pathways of secondary metabolism can be highly complex and highly specific, with single step modifications greatly influencing bioactivity, while causing minimal changes to the physical properties of the molecule. These issues require an integrated approach of extraction, separation and bioassay screen to gain maximum information on functionality and potential value.
3. Enhancing the development of plant secondary metabolites or their derivatives for commercial use, through more efficient linkage between plant product discovery and synthetic chemical engineering and synthesis.
4. Understanding the complex biosynthetic

pathways and flux control: networks of pathways of plant secondary metabolism are such that changing the flux of metabolites in one pathway can impact either positively or negatively on flux to other distant pathways. Thus, the yield of single bioactive metabolites can be difficult to control due to the influence of metabolic context and the adaptive responses of the plant capable of causing massive shifts in flux. Detailed genetic analyses of up- or down-regulating the expression of genes encoding specific enzymes in the pathways of secondary metabolism can start to provide input into flux control, particularly when these analyses are integrated with proteomics and metabolic profiling.

5. Mechanisms for increasing yields of defined bioactives from plants: gaining an understanding of pathway networks and flux control provides the basis for designing new strategies for increasing yields of defined metabolites. This could be accomplished via either a non-GM approach in which TILLING, for example, could take out a step in a competing pathway, or a GM approach in which the level of precursors could be increased by introduction of novel pathways into the transgenic plant, or engineering existing pathways.

Time frame

Five years:
- Genomic knowledge base for selected plant species.
- Coordinated programmes for the discovery of metabolic pathways and products.
- Modification of metabolic pathways to increase diversity and functionality of identified products.
- Establish collaborations with international developing country partners to work on screening programmes of indigenous flora for pharmaceutical purposes

Ten years:
- Proteomic and metabolomic knowledge base for selected plant species
- Progressive regulatory integration of the plant biotechnology sector and the pharmaceutical sector
- Continued development of international developing country partnerships
- Pilot production system for a secondary metabolite product derived from genetic engineering. Establish metabolomic database for targeted medicinal plants
- Application and transfer of European knowledge base to developing countries for humanitarian purposes
- Development of molecular engineering strategies for transfer of the optimisation of secondary metabolism in plants

Twenty-five years:
- Dedicated production platforms for bioactives of high utility
- Identification of molecular engineering strategies for transfer of new metabolic pathways to alternative production systems

Deliverable two: Specialty chemicals and enzymes [Ref.: C2.G1.D2]

Chemicals [Ref.: C2.G1.D2.S1]

Plants offer multiple opportunities as production systems for specialty chemicals for industrial applications, ranging from surfactants and waxes to pigments, flavours and fragrances. Plant products would benefit from biocompatibility and biodegradability. Industrial demand for plant or fermentor derived specialty chemicals will continue to grow in response to consumer trends requiring products that are derived from greener and more sustainable ingredients.

Realising the opportunities of plants in this sector will require research and development to identify and optimise quality and production of the target compound in close co-operation with the end user community. One example is sugar-fatty acid esters that can act as powerful surfactants. These compounds are currently used widely in the chemical industry (e.g. for skin care industry) and are synthesised on an industrial scale using organic solvents.

There are now strong drivers to minimise the environmental impact and deliver products that are derived from natural sources rather than through processes involving organic chemistry. This is particularly the case for products for the health and skin care industries. The properties of sugar-fatty acid ester surfactants vary with the ratio and types of sugars and fatty acid molecules. The chemical industry has already established procedures that involve organic solvents for the production of surfactants. Development of plant-derived surfactants will require close collaboration between the end-user industrial chemists and plant scientists to identify best-candidate surfactants to replace existing products. Some plant species already produce significant amounts of potentially valuable surfactants. For example, Lycopersicon penellii, a wild tomato species, which grows in South America, produces sugar fatty acid surfactant compounds in glandular trichomes and secretes these on to the leaf surface at levels of up to 20% leaf dry weight.

Developing such specialty chemicals could involve rapid domestication of the native species or the transfer of all or part of the biosynthetic machinery from the native species into either a more amenable crop or fermentor-based system. The route chosen will be defined on a case-by-case basis. For instance, with surfactants, it may be possible to rapidly domesticate a native species, whereas with complex secondary metabolites that are active as flavours or fragrances, it may be more appropriate to identify key enzymatic steps in the native species and employ these to perform equivalent or related reactions in microbial fermentor based systems. Similarly, specialty enzymes could be used directly as biocatalysts in conjunction with green chemistry procedures to meet the demand for greener, more sustainable feedstocks. Specialty enzymes are the subject of the next section.

Time frame

Five years:
- Identification and functional characterisation of specialty chemicals, such as surfactants, flavours and fragrances from native species
- Establish best strategy for product development in close collaboration with industrial chemists and end-users
- Establish programme of rapid domestication in those cases were it is considered feasible over a relatively short time period (5-10 years)
- Build on existing knowledge to determine biosynthetic route to product in

native species and clone key genes in the pathway
- Transfer key steps in product synthesis into amenable crop platform or microbial system

Ten years:
- Rapid domestication of target native species for specialty chemical production
- Optimisation of transgenic crops for manufacture of specialty chemicals
- Optimisation of microbial systems for manufacture of specialty chemicals

Twenty-five years:
- Sustainable delivery of a suite of plant-derived specialty chemicals at commercially viable levels from microbial production systems
- Establish and implement agricultural practices for the production of novel crops producing high-volume/low-cost commercially viable levels of industrial enzymes

Industrial and technical enzymes [Ref.: C2.G1.D2.S2]

Industrial enzymes are used in a wide range of large-scale applications, including those for starch processing, detergent manufacture, paper/pulp processing, gas/oil production, textiles, food, beverages and animal feed. At present, some 100 different enzymes are used in these sectors at industrial scale. Several of these, such as the α- and β-amylases, are used in the brewing industry at levels of greater than 100 tons per year. Many other applications typically use under 10 tons every year. More than half the industrial-scale enzymes are encoded by fungi and yeast cells, with about a third encoded by bacterial genomes. Plant sources of industrial enzymes are comparatively limited, but include several of those used in brewing (amylases, β-glucanase and bromelain), and used in food processing (actinidin, ficin and lipoxygenase). Typically, non-microbial enzymes are used in more technical applications, such as chemical analyses, diagnosis and specific biotransformations.

For ease of large-scale purification of microbial enzymes for the industrial sector, secretion from the host production cell is very relevant. Extraction from the fermentation medium is more rapid and straightforward than breaking open cells and purification from the cytosolic mixture. When enzymes are required in purified form, routes to their large-scale production are likely to include the use of recombinant systems. Plant-produced enzymes must also be relatively straightforward to extract and purify for large-scale applications. However, for many industrial uses, purification of individual proteins may not be necessary and plant extracts containing the enzyme and many other protein components may suffice.

The use of enzymes in manufacturing processes is set to expand greatly with the emerging bio-based economy which will involve the transition from the use of mineral oil feedstocks to those produced by agricultural crops and forests. Bio-refineries and extended fermentation facilities will certainly lead to expansion in microbial enzyme applications, but also offer immense new opportunities for increased use of plant-derived enzymes. Processing of biomass and crop feedstocks is one aspect of this changeover to a bio-manufacturing base. Interconversions of biochemicals produced from those feedstocks is another aspect.

Biocatalysis is an important growing technology which offers an environmentally friendly alternative for conventional chemistry. For example, the use of enzymes in aqueous solutions would replace the need for organic solvents. Developments of the technology have been limited by the cost and availability of appropriate enzymes, but plants offer a very productive tool to produce these kinds of enzymes at a very low cost.

Since proteins are direct gene products, transgenic approaches to substantially increase the levels of defined enzymes in engineered plants is a straightforward procedure that offers considerable potential for the development of new industrial crops. In addition, functional genomics is enabling the identification of gene sequences encoding different enzyme classes in many plant genomes. These plant recombinant enzymes can be produced in microbial hosts in large quantities.

Enzyme classes of particular significance include hydrolases, such as lipases, the exo- and endo-peptidases, nucleases and glycosidases. In addition, small molecule plant metabolites, such as products of secondary metabolism, exist as glycosides. The many multigene families of plant glycosyltransferases of these small molecules are increasingly used as regio- and stereo-selective biocatalysts for glycobiology, both as recombinant enzymes and engineered into microbial cells for nutraceutical, pharmaceutical and healthcare fermenter applications.

Time frame

Five years:
- Identification and biochemical characterisation of new plant enzymes for important industrial processes to complement or replace chemical catalysis
- Ising bioinformatics and functional genomics
- Establishment of plant ‘tool boxes’ for the optimal expression of recombinant microbial enzymes

Ten years:
- Optimisation of transgenic crop production for manufacture of industrial enzymes and their extraction

Twenty-five years:
- Replacement of chemical catalysts by design of new bio-catalysts
- Sustainable delivery of a suite of plant-derived enzymes from microbial production systems
- Establishment and implementation of agricultural practices for the production of novel crops producing high-volume, low-cost, commercially viable levels of industrial enzymes

Deliverable three: Plant-derived oils as industrial feedstock [Ref.: C2.G1.D3]

Plant-derived oils are structurally similar to the hydrocarbon chains that give functionality to petrochemicals. Consequently, the potential for plant-derived oils to act as a sustainable replacement to petrochemicals is well recognised and indeed plant oils are already used in a number of non-food industrial applications, ranging from lubricants, polymers, paints and solvents to inks, dyes, cosmetic products and surfactants.

It is widely recognised that both the range

of applications and volume of plant-derived oils being used as industrial feedstocks could be increased further and, in many cases, offer a viable alternative to petrochemical-derived feedstock. The limiting factor is that the range of functionalities offered by plant oils derived from current oilcrops is restricted. Plant oils are major commodities, worth about €40 billion annually worldwide, with food uses making up 80% and non-food applications representing the rest. On the whole, plant oils have been bred for food applications and the range of fatty acids that are represented in the major oilcrops (oilseed rape, sunflower, maize and soybean) is very limited.

Erucic acid and lauric acid are good examples of two plant-derived fatty acids that have been specifically developed for non-food applications. Each of these markets is worth more than €1 billion annually. The challenge now is to develop other designer plant oils which can be used as petrochemical substitutes in industrial feedstock for a wide range of applications.

Plant oils consist of triacylglycerol molecules, each of which is made up of three fatty acids attached to a glycerol backbone. It is these fatty acids that give plant oils their functionalities. There are several hundred unusual fatty acids with useful functionalities that are mostly found in wild species of plants that are recalcitrant to cultivation and only produce these rarer acids at low levels.

Scientists have been successful in identifying key genes responsible for the production of unusual fatty acids in native species and transferring these into various model and crop species. This has proven that it is possible to produce these unusual fatty acids, such as ricinoleic acid and conjugated fatty acids, in transgenic plants that do not normally produce them. However, the proportion of the unusual fatty acids in total oil in the engineered oilcrops is invariably much less than what is found in the native species. For this barrier to be overcome, we need to understand the mechanisms that regulate the introduction of new functional groups into fatty acids and the flux of these unusual fatty acids into triacylglycerol during oilseed development. Most of this partitioning occurs at the endoplasmic reticulum-oil body interface and will require multidisciplinary approaches. Underpinning knowledge of the underlying process needs to be gathered to enable scientists to engineer the production of any one of a number of valuable unusual fatty acids.

An additional factor that needs to be addressed is the viability of seeds that have been engineered to produce unusual fatty acids. Seeds use storage oil reserves to fuel germination and seedling growth. Introduction of unusual fatty acids into the storage oil may, in some cases, limit efficient use of the oil by the young seedling and so compromise growth. This factor needs to be addressed and if necessary, additional transgenes introduced that will allow the efficient utilisation of the novel oil during seed germination and seedling growth.

In addition to industrial feedstock applications, recent developments in the biofuels sector have resulted in a massive growth in the use of plant-derived oils for biodiesel. The main demand for plant oils in the context of biodiesel is to maximise the yield and minimise the inputs to the entire crop, which is predominantly oilseed rape in Europe. Specifically in relation to development of plant oils, the main demand from the biodiesel market is to maximise the flux of carbon and fatty acids into triacylglycerol in order to increase the yield of oil per hectare.
Research and development work can be prioritised, on the basis of the requirements from the different application sectors for plant-derived oils, as follows:

- **Lubricants** (high oleic acid oils and C8-C10 fatty acids)
- **Polymers** (high oleic acid oils, ricinoleic acid, epoxy fatty acids and conjugated fatty acids)
- **Paints and solvents** (conjugated fatty acids)
- **Surfactants and cosmetics** (high oleic acid oil and C8-C10 fatty acids)
- **Inks and dyes** (conjugated fatty acids).
- **Biodiesel** (maximise yield by increasing flux of carbon and fatty acids into triacylglycerol; as well as high oleic acid oils)

In all of these sectors, there is a demand to optimise or modify the fatty acid content and maximise the flux of fatty acids into triacyglycerol in order to achieve high oil yields. Research and development breakthroughs in one sector should also directly benefit other application sectors.

Development of non-food crop platforms [Ref.: C2.G1.D3.S1]
It is generally recognised that production of industrial feedstocks not normally present in the food chain would be best achieved in a non-food crop. This would allow the novel crop to be grown commercially without the added costs associated with segregation of products needed to ensure their exclusion from the food chain. To this end, there is a need to develop a non-food crop platform that could be used for the production of a range of plant-derived oils. The selection depends on the existing performance of the crop, its geographic range, the possibility of 'out-crossing' to food crops, the genetic tools available, etc. Crambe and Brassica carinata are currently recognised as leading candidates for development.

Finally, the possibility of rapid domestication of wild species that are already producing valuable industrial feedstocks but at non-commercially viable levels should also be considered.

Time frame

Five years:
- Identification and characterisation of the major bottlenecks limiting the production of high yields of unusual fatty acids, such as hydroxy, epoxy and conjugated fatty acids in both model oilseed species and oil crops
- Addressing related factors of seed biology, including capacity of engineered seeds to germinate and remain viable in subsequent generations
- Development of strategies to maximise the flux of carbon into oil during seed development in order to maximise the yield of oil per hectare (addresses demand from all application sectors)
- Evaluation of existing oilseed species diversity for functionality and initiation of rapid domestication programmes, if appropriate
- Development of non-food crop platform for industrial oil production – to include transformation and metabolic engineering

Ten years:

- Strategies to remove production bottlenecks for unusual fatty acids at commercially viable levels in oilcrops
- Strategies to eliminate any related traits that compromise the novel crop, such as germination and seedling establishment efficiency
- Optimisation of yield performance of oil crops for different industrial feedstock end uses and biodiesel production
- Rapid domestication of target species
- Employing non-food crop platform for the production of unusual fatty acids, such as hydroxy, epoxy and conjugated fatty acids
- Development of new catalytic activities for fatty acid modifying enzymes in order to produce fatty acids with novel functionalities

Twenty-five years:

- Establishment and implementation of agricultural practices for the production of novel crops generating commercially viable levels of industrial oils
- Delivery of new varieties of oil crops with lower inputs and higher outputs to meet the demands of food, feed, biofuels and industrial feedstock industries

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Deliverable four: Polymers [Ref.: C2.G1.D4]

Starch [Ref.: C2.G1.D4.S1]

Starch is the second major agricultural commodity after cellulose, is the least expensive food commodity, and has numerous industrial applications. Currently, about 25 000 tons per year are converted to biodegradable polymers by a range companies. Most of this bioplastic is marketed as biodegradable and is used for packaging films and foams, as well as disposable goods, such as cups, plates and carrier bags. The growth potential of this market is high, with many studies referring to future market sizes in the range of 1 million tons every year.

Owing to the importance of this commodity, starch has been studied in great depth. Most work on starch modification and improvement was carried out with food applications in mind, but this research is also useful in terms of highlighting the potential of producing thermoplastics from starch.

One of the main barriers to applications of thermoplastic starch is its high moisture sensitivity and difficulties in processing. Such problems can be remedied by chemical derivatisation, for instance, by introducing ester and ether groups, as well as by extensive blending, thermal and physical treatment. To make starch more suitable for bioplastic applications, it should be less crystalline and more hydrophobic.

The long-term goal is to modify starch's molecular weight, degree of crystallinity and to include chemical substitutions to increase hydrophobicity. The blending of starch with other polymers or their chemical building blocks is also a long-term goal needed in order to allow starch to be more widely used as a useful biopolymer. While some of these changes can be reached by chemical modification of native starch, there is a need to develop novel methods to modify starch in *planta*, without compromising the yield.

Time frame

Five years:

- Identification of enzymes (plant and non-plant) that can modify starch structure in vivo, including its molecular weight, branching pattern and introduction of substitution groups
- Enhancing understanding of the starch granule structure-function relationship.

Ten years:

- Demonstration of feasibility of using new enzymes to modify starch in plants
- Establishment of non-food crops for the production of starch possessing novel functionalities for the purpose of biopolymer production
- Introduction of genetically modified plants with enhanced starch structure for use in thermoplastic starch

Twenty-five years:

- Establishment and implementation of agricultural practices for the production of novel crops, generating commercially viable levels of novel starches for biopolymers

Rubber [Ref.: C2.G1.D4.S2]

The production capacity of natural rubber from *Hevea brasiliensis* (the rubber tree), currently estimated at 9 million tons per year, will be too limited to satisfy future demand due to the speed of global economic growth and the long-term goal of replacing non-renewable synthetic rubber. In addition, the rubber tree is essentially a monoculture and is under threat from a pathogenic fungus *(Microcylus ulei)*, which could wipe out 80% of world production.

Therefore, it is necessary to develop alternative sources of natural rubber. While many plants contain natural rubber, only two of these were shown to contain rubber of the same molecular weight as the *Hevea* variety: guayule and the Russian dandelion.

Guayule is considered a viable alternative to the rubber tree because large-scale production has been shown to be feasible (10 000 tons per year in 1910), and the quality and yield of the rubber is close to that obtained from the rubber tree. Commercial production of guayule rubber ended in 1945 when, after World War II ended, *Hevea* rubber became plentiful and cheap. Since then, several attempts were made to restart guayule cultivation during the oil crisis in the 1970s and early 1980s. In the course of these efforts, guayule was partially domesticated, and several productive lines were generated. In addition, agronomy and harvesting methods were studied.

Recently, guayule has attracted renewed attention because many consumers are allergic to *Hevea brasiliensis* rubber, but not to the guayule variety. This has sparked some renewed cultivation of guayule.

The only other alternative to the rubber tree that has been studied in some detail is the Russian dandelion. These studies were conducted during the shortages of World War II, but did not lead to any great breakthroughs. Even under wartime conditions, it was not considered a viable source of natural rubber, mainly due to agronomic considerations, although the rubber quality was very good.

In almost all issues relevant to the production of natural rubber from guayule or Russian dandelion – breeding, cultivation, harvesting, storage, processing, co-product valorization, and applications – there appear to be considerable differences in opinion, even controversy, on issues of best practice. This indicates that

much remains to be done. Moreover, our limited understanding of genes, proteins and metabolic pathways involved in rubber synthesis is quite astounding in view of the tremendous importance of natural rubber for modern society. There is great potential for improvement of practically all aspects of natural rubber production from alternative sources of natural rubber.

Time frame

Five years:

- Establishment of a generic research programme on the molecular biology and biochemistry of rubber production in guayule, Russian dandelion as well as in other rubber-producing plants, such as Goldenrod. This needs to identify the key genes involved in rubber synthesis, in the control of molecular weight and the synthesis of allergenic proteins
- Establishment of breeding and germplasm programmes for guayule and Russian dandelion
- Identification of suitable regions and agronomic practices for the cultivation of guayule and Russian dandelion, as well as the creation of field plots
- Development of efficient transformation systems for guayule and Russian dandelion
- Methods to prevent gene flow from transgenic rubber-producing plants to wild relative (in case of Russian dandelion)
- Life cycle analysis of rubber production in Europe from guayule and Russian dandelion

Ten years:

- Establishment of efficient, economical and environmentally acceptable methods for the harvest, storage and extraction of rubber and the uses of the by-products, including the possible exploitation of bagasse for energy generation and/or bio-ethanol
- Setting up a small-scale production facility for rubber in Europe
- Development of new germplasm with improved agronomic properties for rubber production

Twenty-five years

- Establishment and implementation of agricultural practices for the production of novel crops, generating commercially viable levels of natural rubber to meet consumer demand

Polyhydroxyalkanoates [Ref.: C2.G1.D4.S3]

Poly-3-hydroxyalkanoates (PHA) are a class of polymers produced by micro-organisms, primarily as carbon and energy storage material. The polymer properties depend strongly on the nature of the monomer. They can range from stiff or flexible plastics to soft elastomers and glues. As a group, PHAs are one of the most attractive biopolymers for consumer products, such as bottles, films and fibres, due to their water and air impermeability.

Extensive studies performed over the last 20 years on PHA synthesis and polymer properties have identified the key metabolic pathways, as well as the best PHA for use in large-scale plastic production for use in consumer products. Synthesis of PHA in plants to range of 8-40% dry weight has been demonstrated. Isolation of PHA from plant tissues and use of residues are key issues that need to be addressed.

Time frame

Five years:

- Generic research programme aimed at understanding the regulation of the carbon flux of acyl-CoAs, including acetyl-CoAs
- Genetic engineering of plants for the high-level synthesis (more than 15% dry weight) of polyhydroxybutyrate homopolymer and a polyhydroxybutyrate-based copolymer containing 3-hydroxycayl-CoA of greater then 6 carbons
- Identification of model crop for the synthesis of PHA in plants, substantiated with life cycle analysis

Ten years:

- Establishment of efficient, economical and environmentally acceptable methods for the harvest, storage and extraction of PHA from crop plant and the uses of the by-products, including the possible exploitation of bagasse for energy generation and/or bio-ethanol

Twenty-five years:

- Establishment and implementation of agricultural practices for the production of novel crops producing commercially viable levels of PHA
- Setting up a production facility for PHA in Europe

Monomers and building blocks for biopolymer synthesis [Ref.: C2.G1.D4.S4]

In addition to the synthesis of biopolymers directly *in planta*, agricultural crops can also be used for the large-scale synthesis of monomers or building blocks that can be used for the synthesis of a wide range of polymers through chemical transformation and polymerisation of the biological building blocks. A good example is the use of hydroxylated, epoxidised, or conjugated fatty acids as building blocks for the synthesis of various plastics, including nylons and polyesters. A description of strategic research and development necessary to deliver oil crops containing high levels of these fatty acids for commercial applications is described in section 2.2.1.3 above. Other monomers that could be considered are 3-hydroxypropionic acid, 1.4 diacids (e.g. succinic, fumaric and malic, amino acids, including aspartic acid and glutamic acid, or sugars, such as glycerol or sorbitol).

Time frame

Five years:

- Prospective study, supported by lifecycle analysis, of the chemical building blocks most suited for production in plants versus bacteria/fungi, as well as the identification of non-food plant platforms for such production
- Identification of key enzymatic pathways in microbes, plants and animals which can be used for the synthesis of important building blocks
- Exploratory production of building blocks in model plant systems

Ten years:

- Genetic engineering of plants for the high-level synthesis of chemical building blocks
- Establishment of efficient, economical and environmentally acceptable methods for the harvest, storage and extraction of building blocks from crops and the uses of the by-products, including the possible exploitation of bagasse for energy generation and/or bio-ethanol

Twenty-five years:

- Establish and implement agricultural practices for the production of novel crops, generating commercially viable levels of chemical building blocks
- Implementation of production facilities for chemical building blocks in Europe

Protein-based bioplastics or biopolymers [Ref.: C2.G1.D4.S5]

Three groups of protein-based plastics and biomaterials can be distinguished: 1) Protein co-products of starch or vegetable oil production, 2) Proteins with potential uses in engineering, like spider silk, mussel adhesive protein, collagen elastin, and 3) Non-ribosomally produced proteins such as polyasparate and polylysine.

The first, heterogeneous group consists of the materials that can be derived from natural proteins, usually co-products of carbohydrate and vegetable oil production. Examples include plastics and resins based on zein, soy protein and gluten from wheat.

The increased demand for biofuels may put huge amounts of waste protein on the market that cannot be absorbed by feed production, enabling the development of a protein-based bioplastics industry. There is potential to alter the structural properties of zein and other plant proteins through genetic engineering.

The second group of protein biopolymers that are useful as materials contains natural protein fibres or adhesives that typically consist of short blocks of repeated amino acids. Examples include silk proteins, elastin, and adhesin from mollusks.

These are potentially very attractive materials, but expensive and labour-intensive to produce. Heterologous expression in plants would enable production on a much larger scale, the larger availability opening up new markets.

In addition, genetic engineering can be used to produce completely new materials, such as block copolymers; combinations of different proteins like silk and elastin; completely synthetic sequences with even better properties; and sequences optimised for production in specific plants.

The third group of protein biopolymers consists of non-ribosomally produced polypeptides, such as cyanophycin (a protein-like copolymer composed of a polyasparate backbone and arginine side-groups), produced by cyanobacteria and a few non-photosynthetic bacteria; polylysine, an antimicrobial polymer used as food additive; and polyglutamate, also used in food.

Time frame

Five years:
- Identification of functionalities that can be added to existing commercially abundant storage proteins to improve their properties as biopolymers
- Identification of mechanisms in plants that are used for production of block polymeric proteins in plants
- Establishment of biochemical pathways for the non-ribosomally produced polypeptides in plants

Ten years:
- Identification and introduction of biochemical pathways involved in the production of storage proteins with novel functionalities into appropriate crop plants
- Optimisation of plant production systems for the production of block polymeric proteins
- Optimisation of plant production systems for the production of non-ribosomally produced polypeptides

Twenty-five years:
- Establishment and implementation of agricultural practices for the production of novel crops, generating commercially viable levels of protein-based polymers

Deliverable five: Fibres [Ref.: C2.G1.D5]

Improvement of plant fibres [Ref.: C2.G1.D5.S1]

Innovations in fibre applications are underway in textiles, bio-based composites, specialised (hybrid) non-woven fabrics and other materials. For the various applications, it is important to gain control of fibre characteristics, which in turn are determined by cell wall composition and the interaction of cell wall components. Functional genomics projects are running to develop a comprehensive understanding of the genetic mechanisms that control *in planta* cell wall development and, consequently, regulate important fibre properties.

Molecular control of cell wall biosynthesis

The knowledge of how the molecular control of plant cell wall biosynthesis is organised is still limited. Plants show a large spectrum of cell walls where e.g. cotton fibres have a cell wall consisting for over 98% of cellulose and are almost devoided of lignin while wood fibres contain relative low amounts of cellulose and over 20% lignin. Recent studies, exploiting molecular genetics in Arabidopsis, poplar, maize and other plants, have identified sets of genes involved in the synthesis of cellulose, pectin, xyloglucans and galactomannans and other cell wall components. Basic knowledge about the molecular control of cell wall biosynthesis is developing. However, there is still a large gap in knowledge about the molecular processes underlying cell wall biosynthesis. More basic research is required to gain insight in cell wall biosynthesis which in time will allow to develop tailor made plant fibres.

For cotton and bast fibres, it is especially important to gain a better understanding of the relationship between the fibre properties and the biochemical pathway and genetic basics leading to it. Fibre strength, fibre length and micronaire are important properties of the fibre. There is still a lack of understanding of fibre development which has to be overcome in order to optimise fibre characteristics. Everything which helps to elucidate the complex genetic and biochemical background of fibre formation is of high value to the cotton and bast fibre industries because it would enable them to deliver fibres corresponding to the high demands of the textile industry.

Wood derived cellulose is seen as an important future source of energy. Several approaches work on the enzymatic conversion of cellulose into glucose and its further fermentation to ethanol. The highest technical hurdle is the step from the cellulose to the glucose monomers because the cellulose fibres are highly crystalline and very difficult to degrade. One area of interest is the relationship between cellulose fibre properties and fibre formation. This would be the basis for modifying the cellulose in such a way that an easier conversion could be achieved without affecting the mechanical stability of the plant itself. Current approaches only tackle the enzymes used for the cellulose degradation and try to improve their performance.

Besides its use as a source of bio-ethanol, wood-derived cellulose is mainly used in the paper industry and as a raw material

for chemical modifications. All processes have one factor in common: the cellulose fibres have to be free of lignin. The separation of lignin and cellulose is an established process but has a lot of environmental disadvantages.
One useful avenue of investigation would be the full elucidation of the biochemical route of the cellulose formation in the context of lignin synthesis. This would help to build a better understanding of how both compounds depend on each other in the mature plant. This would provide the basis to modify the cellulose and lignin content of the plant in such a way that the cellulose can be separated more easily. This approach is also applicable to produce nano-fibres that can be applied in high value-added composite materials.

On average, the specific tensile strength of the strong bast fibres is comparable to glass fibres, but the best values found by single fibre measurements are much higher and almost comparable to aramide fibres. At present, there is no process available to separate the strongest fibres from the bulk. Even if such a process existed, the yield would be much too low to be economically feasible. Research should focus on the interaction between the natural fibres and the composite materials. Factors to consider are fibre shape fibre array and orientation, as well as fibre matrix adhesion.

Towards
novel plant fibres [Ref.: C2.G1.D5.S2]

Biotechnological approaches

1. Cellulose based biocomposites are limited by poor interfacial binding between the polyhydroxyl fibre surface and the hydrophobic matrix component. It has been shown that *in vivo* modification of fibre surfaces could alter their properties and enable them to bind to matrix materials. Applied *in planta*, such an approach would yield a whole new range of functional groups on natural fibres.
2. Cell length might be modified by expansins. Experiments using transgenic plants have indicated that it is possible to modulate cell expansion through manipulation of expansin expression. It can be expected that high expression of expansins in fibre cells will increase cell elongation, thereby yielding longer and thinner fibres that are of high interest to the fibre industry.
3. New functionalities can be created through the production of biodegradable polymers inside a natural fibre. Introduction of low amounts of poly-hydroxybutyrate (PHB) in the lumen of flax fibres already resulted in significant modifications in Young's modulus E. [50]. With improved gene constructs and additional research, this approach shows high potential for various applications in a number of fields including composites, where the inherent polymer promises improved adhesion and strength.

Time frame

The following research activities should be undertaken to tackle the issues covered by both scopes in deliverable five, goal one, challenge two.
Five years:

- Increased knowledge of cell wall development in relation to fibre properties
- Development of novel plant fibres for textile applications
- Composite materials incorporating a variety of plant fibres

Ten years:

- Improved fibres for adding functionality to composite materials
- Development of longer, thinner fibres by modifying cell length
- Development of stronger fibres by modifying the plant cell wall
- Plants with modified cell walls with easy extractable fibres
- Simplified procedures for extracting plant fibres from the natural source

Twenty-five years:

- Tailor made easily extractable fibres with enhanced properties for specific applications

Goal two: Bio-energy production

[Ref.: C2.G2]

The supply of plant-derived bio-energy – which currently provides less than 1% of our energy requirements – is expected to increase dramatically in the coming decades. This bio-energy is provided either directly through simple combustion, primarily of wood products, or after the conversion of agricultural biomass from a variety of plant sources into different liquid and gaseous biofuels, such as bio-ethanol, biodiesel and biogas. The trigger for the rapidly growing demand for bio-energy was the huge oil price increase of 2004. This made biofuels derived from agricultural products, such as cornstarch, cost-competitive with petroleum-based fuels and initiated an irreversible shift in the global economy from fossil fuels to renewable energy sources.

Furthermore, the shift towards biofuels and renewable energy is driven by the rapidly growing consensus that global warming is in part caused by the release of fossil fuel-derived carbon dioxide, concerns regarding the security of energy supplies and shrinking fossil fuel reserves. The use of renewable biomass-based fuels has the potential to be CO_2-neutral or even reduce CO_2 levels. This, together with the recent biofuels policy support measures in both the EU and the United States, has triggered the explosive development of a first generation biofuels industry.
In the USA, the large-scale development of biofuels beyond the current level is supported by a national road map for biofuels and the allocation of several billion dollars of structural funds for research and development. In the EU, the continued growth of the biofuels industry will be driven in the coming years by the recent Biofuels Directive which sets targets of 5.75% and 25% market shares for transportation fuels derived from biomass and blended with fossil fuels in 2010 and 2030 respectively. To illustrate the magnitude of these reference values, if the 2010 target is to be reached via the cultivation of oilseed rape, Europe would have to set aside six times the current acreage for this crop, raising it to 5 million hectares.

The key technological challenges for the production of renewable biomass-based fuels are all related to optimising the cost-efficiency of biofuel production, namely biomass yield, nutrient and water-use efficiency, and energy conversion efficiency.

The first generation of biomass fuels, that are currently produced, are derived from special biomass feedstocks that are efficiently converted into biofuels that can be blended directly with fossil fuels as transportation fuels. These feedstocks are either sugars or starches which are fermented into bio-ethanol or vegetable oils that are then converted into biodiesel. The first generation biofuel crops are in fact food and feed crops, such as wheat, corn or oilseed rape which have been optimised for food or feed production, but not for biofuels. Hence, neither the biomass yield nor the input requirements are optimal. Furthermore, the net energy balance – i.e. the ratio of output to input energy – of these first generation biofuels is far from ideal.

The second generation biofuel crop species – dedicated energy crops – will be tailored specifically to the production of biofuels with optimised biomass yield and input requirements, such that their net energy balance is substantially improved. This optimisation will be achieved by defining the key biological processes that underpin biomass yield, and water and nutrient use efficiency.

It is generally envisaged that the second generation energy crops will produce primarily lignocellulosic feedstocks that will be fermented into bio-ethanol using novel saccharification and fermentation technologies. The principal challenge here will be the development of efficient biomass conversion technologies for lignocellulosic material.

To ensure that the economics behind the future energy crops and the associated bio-refineries works, the opportunities presented by by-products, residues and waste should be explored.

In addition to the dedicated biofuel energy crops, improved tree crops will provide renewable bio-energy through simple combustion. It is expected that the plant resources used for energy supply will reflect geographical location (such as forestry, grasses and field crops).

The sustainable production of biomass fuels must take into consideration the environmental impact and societal acceptance of such energy sources. While the environmental impact of the first generation biofuel crops is substantial, the envisaged improvements in the cost-effectiveness of energy production, namely the reduced input and water requirements, will significantly improve the environmental impact. The second-generation biofuel crop species will, by virtue of their minimal input requirements, also have a highly reduced environmental impact, and will contribute to preserve biodiversity. With regard to societal acceptance, many stakeholders are convinced that the stage is now set for the large-scale production of green energy which will constitute the main driver in the emerging bio-based economy. The technological improvements will only expedite this development process. Furthermore, it should be stressed that this mass production will provide new rural employment opportunities which are especially important in light of reforms to the Union's Common Agricultural Policy, especially in new Member States where pressure on fragile rural communities is greatest. However, the production of green energy will also face the exceptional challenge of global industrial restructuring in which the very different value chains of agricultural production and the biorefining industries must be merged with the value chains of the energy providers.

Today, the lead market for biofuels is primarily supported by tax incentives and other forms of government subsidies – measures which are not sustainable in the long run. Biofuel production in Europe can be cost-competitive on the international market provided that high-tech energy crops

are grown. These should be adapted to the different climatic regions and optimised for sustainable biomass yield under low-input agriculture.

High-tech energy crops will most likely be based on the application of plant biotechnology and genetic modification, which could be inhibited by the rigidity of current GM regulations in Europe. This problem can be addressed either by developing a new European regulatory framework or by adapting the implementation of the present GM regulation for non-food crops. The mere fact that energy crops will help to mitigate the effects of climate change should be used to raise broad public support and acceptance of GM energy crops.

Ultimately, the economic competitiveness of plant-based energy production may only be achieved by combining energy production with the production of biochemical feedstocks so as to maximise the economic value of agricultural production. This will entail the development of a third generation of biofuel crops – multi-purpose crops – which can produce specific biochemicals, as well as biofuel from lignocellulosic material.

At present, it is only possible to outline broadly how the large-scale production is likely to unfold – i.e. which technologies could become competitive and what mix of conventional crop species and novel dedicated energy crops could be deployed in the different European agricultural regions. At this stage, it is important to support a broad range of technological developments that will enable the European bio-energy industry to implement the most optimal green energy production systems on a local basis.

Deliverable one: Production of biomass [Ref.: C2.G2.D1]

Currently three different types of plant resources are considered for biomass production:

- **Field crops producing sugar, starch or oil feedstocks**. These are the first generation of biofuel crops.
- **Tree crops for bioenergy**. Fast-growing trees as energy crops can be grown in Europe as short rotation coppice: willow (Scandinavia and the British Isles), poplar (central Europe) and Robinia (Mediterranean Europe). Harvests take place after leaf fall in winter in a cycle of two to five years. The established root system and the nutrients stored in the roots and stumps guarantee vigorous growth for the shoots. Plantations yield from 8 to 20 tons of dry woodchip per hectare per year. A plantation can be harvested for up to thirty years before needing to be replanted.
- **Dedicated energy crops for producing lignocellulosic feedstocks.** This will be the second generation of biofuel crops. Perennial grasses show many beneficial properties as energy crops, and have been evaluated as bioenergy feedstocks in both the United States and the EU. A large number of perennial grasses have been grown or tested as energy crops in Europe. Mostly funded by the European Commission, research has focused on four rhizomatous grasses: reed canary grass (C3, northern Europe), *Miscanthus* (C4, central and southern Europe), switchgrass (C4, central and southern Europe), and Giant Reed (C3, Mediterranean Europe). These energy crops can be harvested in late autumn to early spring, when nutrients are stored in the rhizomes. Annualised biomass yields reported range between 5 and 40 dry tons per hectare each year.

The principal technological challenges for improving the production of these three types of plant resources for biofuel and bioenergy production are to boost biomass yield and improve the efficiency of water and nutrition use, as well as enhancing the composition of lignocellulosic feedstocks for biofuel production.

Increased biomass yield and improved efficiency of water and nutrition use [Ref.: C2.G2.D1.S1]

Biomass yield is one of the key success factors for lignocellulosic energy crops. The challenge is to improve both the yield and the yield stability of energy plants. This will be achieved by screening the available biodiversity for highly productive species and analysing the genetic variability within species. Another approach will be to extend the genetic variability by genetically engineering for improved traits, such as dry matter and energy yield, source-sink interaction and stress tolerance. A third means will be innovation in crop production, in particular the development of regionally adapted energy crop rotation systems which allow maximum fixation of solar energy during the whole vegetation period.

The enormous potential of innovative plant breeding and crop production approaches has not yet been explored. It is expected that the yield of dedicated energy crops for whole plant fermentation can be increased by up to 100% within the next decade.

The key factors driving high-yield crops are the availability of water, nutrients and sunshine. Most climate change models predict significantly drier summers within Europe for the coming century. Since most of the growth, even of perennial crops, happens during this period, the increased efficiency of water use will become ever more necessary.

The challenge to meet the demand both for food and for fuel is to generate the highest yields in terms of biomass with the lowest water and nutrient inputs over a wide range of geographies, both for conventional field and energy crops. Comparative studies of the genetics and physiology of different types of crops are needed to establish the basic principles for improving the efficiency of water and nutrient use. To elucidate these basics, research should focus on genetic diversity and plant physiology.

CO_2 neutrality or even absorption are exciting possibilities for biofuels derived from lignocellulosic biomass. This does, however, require limited inputs in the sense of energy expended, such as diesel fuel needed for such things as crop protection and the spreading of fertiliser. Net reductions in atmospheric CO_2 are possible when energy crops fix significant amounts of carbon in stable structures, such as lignin and cellulose, which remain after harvesting, for instance in the root system. Special attention should be given to identifying energy plants which possess this property.

To achieve the projected yield improvements, it will be important to develop basic genetic and genomic tools for trees and energy crops. Genetic diversity in trees and energy crops has only been studied in a limited fashion. For such crops as *Miscanthus x giganteus*, no genetic diversity is available at all. Therefore, it is first necessary to collect and then develop genetic diversity for both trees and perennial grasses. Study of this genetic diversity will help lead to the discovery of the basic principles for biomass yield, as well as the efficiency of water and nutrient use. The poplar genome of one representative variety has been sequenced and switchgrass sequencing has been initiated in the United States. It makes sense for Europe to focus on the other energy crops. Equally important is the development of genetic transformation to enable directed alteration of beneficial energy crop properties. Switchgrass transformation has been established in the USA. Again, Europe needs to focus on the other energy crops.

Finally, it will be important to identify portfolios of energy crops that are fully adapted to local climatic conditions. To deliver high fuel yields across a wide variety of geographies, the best regional energy crops need to be identified. This can be achieved in head-to-head comparative studies of energy crop genetic diversity in across the EU.

Time Frame

Five years:
- Genetic diversity established for selected energy crops
- Sequencing of selected energy crops completed
- Transformation technology developed for each of the key energy crops
- Plant physiology and yield screens developed

Ten years:
- Results from plant physiology and yield screens of genetic diversity over various geographies suitable for the respective energy crops will allow correlation between genotype, plant physiology and biomass yield

Improved composition of lignocellulosic feedstocks for biofuel production [Ref.: C2.G2.D1.S2]

Another challenge is to provide plant biomass specifically adapted to sophisticated conversion technologies. This will be achieved by increasing the dry matter content of energy cropsand maximising the content of energy-rich compounds, Another means would be to improve the digestibility of plant biomass in technical or microbial conversion processes through the use of innovative strategies for post harvest-induced catabolism to release fermentable sugars from polymers, such as cellulose. In addition, the high dry matter and energy content of energy crops will reduce the cost of transporting and storing feedstock. The induced breakdown of polymers will help to reduce fermentation time.

An important goal for the development of energy crops is to increase the fuel yield by improving the biomass for subsequent processing. White biotechnology offers a promising route to turn biomass into transportation fuels. Biomass is first subjected to pre-treatment (such as heating it or adding dilute acid) in order to make the cellulose and hemicellulose fibres accessible for subsequent saccharification using cellulases/hemicellulases. Improvement of the biomass such that subsequent processing delivers high fuel yields is one of the keys to reducing production costs of fuel from lignocellulosic biomass. During fermentation, C6 sugars can be more effectively utilised compared to C5 sugars, whereas lignin remains a leftover that can be combusted to generate process energy and electricity. Enhancing the cellulose of lignin ration and the cellulose over hemicellulose ratio are promising approaches to increasing fuel yields, because they act in a synergistic fashion, both on saccharification and on fermentation yield. Alteration of the ratios of the different subunits in lignin offers additional potential for further fuel yield increases.

The transportation cost of lignocellulosic biomass per unit of stored energy is significantly higher than that of sugar, starch or oil-based biomass. Most US analyses indicate a maximum transportation distance of 50 kilometres from the processing plant. In order to reap the benefits of the significant economy of scale in a processing plant, a large volume of biomass needs to be transported. This is preferably done at low costs, and thus over short distances. This drives the needs towards energy crops having a very high yield per hectare. In addition, land available for agriculture is limited and a significant share of it will be needed for production of food and feed.

Deliverable two: Conversion of biomass [Ref.: C2.G2.D2]

The primary challenge will be the development of efficient technologies for the conversion of biomass into biofuel, using both improved lignocellulosic feedstocks and improved enzymes for saccharification and fermentation to ethanol or other biofuels. While the former is discussed in the preceding section, the latter falls under the remit of the Industrial Biotechnology Technology Platform. In essence, biorefinery improvements will involve improving the efficiency of conversion technologies and the purification of conversion products.

The challenges for improving the efficacy of the conversion processes will be to increase conversion rates and to obtain pure products. This will be achieved by increasing the substrate load of fermenters (dry fermentation). This will entail improving energy efficiency, such as achieving catalysis at low temperatures. It will also involve improving the technical and microbial digestion and conversion of substrates; optimising micro-organisms and enzymes, including broad substrate spectra and high conversion rates. Advanced enzyme preparations and defined microbial inoculates, including novel strains obtained through genetic engineering, will improve turnover rates and thus the overall efficacy of second generation bioethanol and biogas production.

The advanced purification of conversion products requires the development of simple and effective procedures to obtain pure preparations of the conversion products. This will be achieved by improving high throughput separation technologies; developing innovative concepts for improving energy efficiency, such as the use of plant residues including lignin as lubricants. Pure product preparations will then be suitable for different uses and also for the synthesis of bulk chemicals for the polymer chemistry.

Deliverable three: Innovative concepts for whole plant utilisation [Ref.: C2.G2.D3]

The challenge here is to exploit all plant compounds. This will be achieved by es-

tablishing zero waste concepts, which allow utilisation of all plant compounds. This also involves closed nutrient cycles; processes for purification of by-products; and the synthesis of novel, value-added compounds in GM plants, such as technical enzymes or fine chemicals.

Commercialisation of all products, including novel value-added compounds from 'intelligent plants', will give European bioenergy production a competitive global advantage. This will contribute significantly to a sustainable knowledge-based bio-economy and the socio-economic stabilisation of rural areas in Europe.

Another important direction is the development of multifunctional energy crops which produce value-added chemicals, such as dicarbonic acids, which can be used for the production of polymers or oils used in the production of lubricants. The value-added chemical will be extracted in an upstream process. The rest of the plant will be utilised for fuel production. Such multifunctional energy crops represent a powerful way of enhancing the economies of sustainable bioenergy production.

Goal three: Enabling research for plant based products

[Ref.: C2.G3]

The overall objective of this goal is to optimise plants to enable them to perform as efficient 'green factories' for the production of biochemicals and energy as described in the first two goals.

Deliverable one: Development of production platform crops and extraction processes

[Ref.: C2.G3.D1]

To realise the potential of crops as production platforms for the wide range of products described in the preceding text, it will be essential to develop crop platforms optimised for single or multifunctional uses. In some cases, this will necessitate the development of non-food crop platforms. For many potential non-food crops, such as those for energy use, the species have not been optimised for their agronomy nor the yield of the feedstock products. This is relevant to perennial grasses, trees and species that have not been developed as crops, but contain interesting compounds, such as unusual fatty acids.

Plant species for the production of specific compounds should be selected based on multiple criteria. These include the availability of appropriate storage organs; the availability of the pathway and compounds of interest; their productivity and the likelihood of out-crossing. It will also be important in developing platform crops to determine the most appropriate for specific geographical regions, as well as ensuring large scale cultivation can rely on low inputs and tolerance to drought.

For platform crops with economic and environmental potential, robust methods for genetic transformation will need to be developed in order to introduce new traits. Furthermore, a detailed understanding of the plant species at a proteomic and metabolomic level is an absolute requirement. Thus it will be necessary to develop a comprehensive range of molecular genetic toolkits. These will enable us, for example, to drive transgene expression in temporal and spatial patterns for over and under-expression of specific genes. This approach will also be used to improve transport, secretion accumulation and storage of the target gene products. Overall, this will necessitate development of both generic toolkits for a variety of crops, such as cereals. In other cases, it will require the development of species-specific toolkits that can be employed in a single species.

Where the selected plant species is a new or marginal crop, conventional breeding for increased yield will contribute significantly to increased compound production. For a crop where advanced breeding material is already available, specific efforts can be made to increase the size of the compound production or storage organs. In this respect, controlled boosting of plant cell division rates would be a valuable tool to maximise the productivity of the plant. Although we are now starting to understand several of the components that regulate plant cell division, it will still require a significant research effort before we are able to control cell division such that the size of specific organs or cell types is changed on demand.

Large-scale production of the selected compounds will require the development and availability of large-scale extraction methods. For several types of compounds – such as fatty acids and polysaccharides – methods can be variants on existing extraction protocols. For others, new extraction methods need to be developed. However, in all cases, it will be desirable to use techniques that are not dependent on hazardous chemicals and solvents. These methods will first be tested at small scales and later adapted for large-scale commercial applications.

Time frame

Five years:

- Choice of candidate plants to serve as starting point for conversion into green factories
- Detailed genomic, proteomic and metabolomic understanding of candidate plant species – a molecular toolbox for each plant production candidate
- Development and validation of biotechnological tools for new production crops
- Improved plant gene expression technologies
- Improved mRNA production and translational performance of mRNAs
- Developing efficient molecular evolution technology
- Developing gene replacement technology
- Improved promoter technologies
- Determining the optimal site of accumulation for groups of non-plant target compounds
- Developing technologies to optimise the targeting of compounds to specific sub-cellular locations
- Developing technologies to optimise the targeting of compounds to specific plant tissues
- Developing scale-down technologies for efficient testing of extraction procedures
- Controlled boosting of plant cell division rates

Ten years:

- Detailed functional understanding of the plant secretory pathway
- Tools to manipulate the plant endomembrane system, storage vacuoles and structures and optimise protein folding and post-translational modification technologies in plant production systems
- Compound extraction technologies for commercial use and applicable to multiple plants and plant cells

Deliverable two: Systems for plant production

[Ref.: C2.G3.D2]

The production of new compounds will require the development of new systems for plant production to achieve commercially sustainable levels. Plant systems will be developed on a case-by-case basis, depending on the target compound for production. They might be plant-based, fermentor-like production systems similar to those conventionally used for recombinant compounds, or they could utilise production crops of whole plants.

In order to allow an orderly transition from research scale to production scale output, it will be necessary to anticipate the completion of product research development and put in place manufacturing strategies and production capacity for the non-food products of plants. This should include rapid production systems for biochemicals, including scalable contained systems (such as fermentors, hydroponic systems, and greenhouse containment facilities), as well as specialist, open environment, farmland facilities. This will lead to the establishment of standard operating procedures (SOPs), process engineering and instrumentation that will facilitate the manufacture of plant-derived products and the regulation of such processes. Ultimately, it will assist in the integration of specialist product farming into the agricultural economy.

In the long term, the increased demand for agricultural land will require increased productivity and extraction efficiency. For this demand to be met, it will be necessary to develop multifunctional crops that can be processed in integrated biorefineries in which the utilisation of feedstock is maximised. For example, in the case of biomass crops, in addition to serving as a source of lignocellulose, feedstock could also be used as a platform for the production of specific biochemicals that represent in their own right, high-value industrial feedstocks. Targets for development will include changing the quality and quantity of specific raw materials, as well as enhancing their processing characteristics.

Achieving optimised feedstock will demand the integration of the full range of biological, chemical and physical disciplines. Systems approaches will be required to identify key control points regulating product accumulation and variability in product quantity and quality in response to environmental conditions in the field.

In order to identify relevant traits for improvement, it is also essential that there is extensive engagement with end users to ensure that only genuinely useful projects are developed.

Time frame

Five years:
- Development of new manufacturing strategies (for production, extraction and processing)
- Development of small-scale manufacturing infrastructure and capacity (such as containment greenhouses and bioreactors to facilitate the entry of plant pharmaceuticals into initial human clinical trials)

Ten years:
- Development of large-scale production capacity (such as containment greenhouses or open environment specialist farmland facilities)
- Scientifically established and validated protocols for coexistence of food and non-food crops

Challenge three: Sustainable agriculture, forestry and landscape

[Ref.: C3]

Agriculture and forestry have always been dedicated to providing humanity with food, animal feed and biomaterials. For centuries, cultivating more and more land has been the traditional answer to addressing the growing needs of the population. However, the volatility of agricultural systems and their vulnerability to the elements has meant that supplying the nutritional needs of the human population has never been an easy task. Deadly famines have marked the history of Europe. For instance, in Ireland, the destruction of the potato crop by a *Phytophtora* fungal infestation in 1846-47 led to the death of more than one million people. Thanks to the technological evolution (agronomy, machinery, genetics, etc.), the so-called Green Revolution allowed a steady increase in agricultural production that outpaced population growth, leading to surpluses in the last part of the 20th century. Some believed that the world's agriculture would forever be able to produce a surplus and the problem would revolve around the geopolitics of distribution.

Although starvation is a thing of the past in Europe, some parts of the world still suffer from periodic famines and some 800 million people (13% of the world's population) are malnourished. Although this is currently largely a question of localised shortages and an ineffective global system to fill them, the situation looks set to change in the coming decades. According to the Academy of Science for the Developing World, the projected increase in population over the next 50 years will put extra pressure on agricultural land, especially in developing countries, possibly leading to global shortages.

Cereals, which provide more than 70% of the world's food supply, play a dominant role in agricultural systems. The intensification of wheat, rice and maize cropping systems has been largely responsible for a doubling in world production in the past 40 years, rising from 1 billion tons in the late 1960s to nearly 2 billion tons in 2006. However, looking at the production/utilisation balance during the past seven years shows that world production reached a plateau of around 1.85 billion tons, while utilisation went up by 25 million tons a year. Utilisations began to exceed production in 2000.
For the last seven years, production exceeded utilization only one year. As a result, world security carryover went down dramatically, from 500 to 300 million tons, even after the largest-ever global harvest of cereals (2 billion tons in 2004). In 2006, the global stockpile fell by 50 million tons, from 350 million to 300 million tons, and the carryover has dropped down to less than two months consumption. If this situation continues, a future shortfall in food availability can be predicted. To guarantee future food security, output needs to be boosted significantly.

Today, urbanisation is encroaching on agricultural land and forests, while reservoirs of new land are very limited. Furthermore, farmland is being degraded in too many countries. In fact, arable land is losing its fertility owing to salt accumulation, soil erosion and, in some cases, desertification or poisoning by xenobiotics. Thanks to European farmers' skills and implementation of new techniques, land fertility potential has been maintained at a good level in the EU.

Therefore, continuing to maintain this potential just by reducing production is not a sustainable option, since Europe cannot stand as a global importer of food and feed in the middle of an ocean of malnutrition.

A new source of concern is global warming. After numerous years of controversy, there is now a consensus among the scientific community on the issue (as illustrated by the recent reports produced by the Intergovernmental Panel on Climate Change). There is already evidence that this process has detectable consequences on agriculture. Grape harvests, as well as blooming times, for wine production are occurring earlier. Of graver concern are the unpredicted shortages in rainfall, which can impact significantly on crop yield, as well as put pressure on irrigation systems. It is estimated that an average 1ºC increase in temperature pushes vegetation 100 km north of its original growth area.
This process is expected to have a significant impact on regional agriculture, leading to local production shortages, as occurred with wheat last summer in Australia. It is also likely to accelerate the rate of desertification in southern Europe but create new opportunities for agriculture in northeastern Europe. A major impact on wild plant species is also expected, leading to the need for the active conservation of biodiversity. Ancient forests may be particularly at risk from global warming.

Whatever the causes of climate change might be, many stakeholders believe that improvements in plants and crop management will provide useful solutions (such as plants able to use water more efficiently and which can endure periodic water shortages). In addition, to help cut the use of fossil fuels, plants will become a source of renewable biofuels, whether it is from cereals, oil seed, sugar beet or sugar cane, contributing to reductions in carbon dioxide emissions. Improvements in plant productivity will help avoid potentially major shortages of food and feed supply, as more crops are diverted to non-food uses and environmental pressures mount.

Coming generations of technologies are likely to provide new tools to take up these challenges. In the future, European farmers should use more diversified crops, producing more and better quality food and non-food products, while reducing their consumption of agri-chemicals, fertilisers, water and energy.

Comparable developments are expected in the forestry sector: the UN's Food and Agriculture Organisation (FAO) projects a 25% increase in the demand for wood between 1996 and 2010. In addition, urbanisation, population growth and the conversion of forests into agricultural land have reduced the available forest cover from 1.2 ha per capita of world population in 1960 to 0.6 ha in 1995, and a further decrease to 0.4 ha is expected by 2025.
This means further deforestation, which is associated with a loss of biodiversity and natural resources, appears to be on the cards. The increasing demand for forest products can be met by boosting the yields of conventional forests through enhanced trees and intensively managed forest plantations.

Back to the sixties
From the 1960s – when the Common Agricultural Policy (CAP) began – until the present, tremendous progress has been achieved. Plant productivity has been significantly improved in Europe, while the level of quality has been maintained and even increased. The average yield of cereals went up from 2.5 ton/hectare in the mid sixties to 5.6 t/ha in 2002 (EU-15). However, if the challenge of improving productivity and quality has been addressed for the main European crops, a lot still has to be done globally (figure 1).

During the early stages of the 'Green Revolution', farmers were advised to maximise the use of inputs, especially fertilisation and plant protection chemical products, so as to maximise production – this was more or less the common rule until the 1970s. The development of integrated management systems heralded the advent of optimising the use of inputs, leading to improvements in the use of water, nitrogen, herbicides and pesticides. The right quantity at the right time is the common rule today. The trend in the consumption of fertilisers and plant protection chemicals reflects these changes (figure 2).

Farm size and the size of individual fields have increased significantly over the past 40 years. The removal of hedges and water drainage have led to a significant increase in land productivity, but they have also resulted in a significant reduction in biodiversity in farming areas, especially in terms of wildlife, with some exceptions.

The European situation
It is a little known fact that the European Union imports €66.6 billon worth of agricultural products and exports only €55.7 billion. The EU is often accused of overproducing and dumping agricultural products, and cereals exports are highlighted as an illustration.

The situation is far more complex than it first appears. The EU is a net importer of agricultural plant products. It is true that the EU currently produces more cereal crops than needed for its domestic consumption. In 2006, 245 million tons were used for domestic needs (245.5 million in 2005) out of a total output of 315 million tons (327 million in 2005), with an average yield of 5.6 tons per hectare. Therefore, Europe had a positive cereal balance of about 30 millions tons on average, which represents an equivalent of nearly 6 million hectares. However, the EU has decreased the amount of cereal it exports (22 million tons in 2005, down from 30 million in 2003). Furthermore, the EU has a large negative balance for oil and protein crops, which represent an equivalent of 16 million hectares (based on net imported quantities and an average yield of 2.3 t/ha). Therefore, the fact that the Union still exports a limited amount of subsidised cereal crops should be balanced against these huge imports of oil and protein crops. Furthermore, the EU is implementing a gradual process of decoupling subsidies and output so as not to distort prices.

Since world demand is forecast to grow steadily, the EU will need to contribute even more to world global supplies. This will entail significant yield increases for European crops. Wheat is often considered to be a European crop. As a matter of fact, European wheat yields are the highest worldwide (5.7 t/ha in 2004 for the EU and 7.8 t/ha and 7.6 t/ha respectively for the UK and

France). Higher levels of research investment explain the higher performance of the UK and France. However, the yield potential still exceeds current levels and plant genomics can help boost it further.

Crop plants are increasingly designed (plant breeding) and grown (farming techniques) to meet the specific requirements of the food and feed industries. The range of quality demands has also increased dramatically. Nutritional value was for long the only driver. It is no longer the case: today we also have to address the functionality issues of a given crop. Varieties of wheat adapted to the bread, biscuit or starch industry differ markedly, and need specific breeding schemes, leading to different technological properties of the harvested seeds.
A range of new tools and techniques allowing plant breeders to create suitable new varieties is now available to reach these goals.

While more recent plant crop varieties have also been bred to enhance genetic tolerance and resistance to various biotic and/or abiotic factors, there is still a lot that remains to be done, such as improving the water and fertiliser efficiency of plants. Plant genomics makes available new tools that can help to reach previously distant goals.

To increase the productivity of more diversified crops and trees on a sustainable way requires the development of tools to characterise and monitor biodiversity in the field and the surrounding wild areas. A better knowledge of the biodiversity of pests and pathogens is also needed to develop crop protection strategies. Finally, plant biodiversity can also be used as a resource to domesticate new crops and trees for plantation forests, as well as to broaden the range of available food.

Forests – which cover one-third of Europe's land surface – also play a vital role. The forest sector is made up of about 15 million forest owners.
It employs around 4 million people and generates some €600 billion in annual business in the EU. In forestry and related industries, such as paper production, the Union is a world leader.

Nevertheless, the role of the forest sector varies substantially across Europe. EU Treaties make no provision for a comprehensive common forestry policy. However, the management, conservation and sustainable development of forests are vital concerns of existing common policies, such as the Common Agricultural Policy, as well as rural development, the environment, trade, internal market, research, industry, development co-operation and energy policies.

Europe's place in the sustainable world of the future

As highlighted earlier, Europe is a net importer of foodstuffs, and not only of products which are grown in developing countries. While coffee and cocoa are well known imported products, new markets are developing: Chile and South Africa are increasing their fruit exports to Europe; and other countries, notably Colombia and Kenya, are world leaders in the production and export of ornamental crops. China is gradually abandoning field crops, such as cereals, to become more involved in the production of vegetables and fruit, where high labour requirement give it competitive advantages. China, for example, is the world's largest producer of vegetables and apples.

However, population growth in the coming decades will put extra pressure on agricultural land in developing countries as they struggle to feed their citizens. One of the implications of this evolving situation will be that Europe will not be able to depend on the emerging and developing world to meet its growing appetite for agricultural products. In fact, it should boost its food and feed output to help satisfy growing global demand.

For their part, developing countries will have to bolster yields, but these increases should be achieved using sustainable agricultural practices, especially as many developing countries are already farming marginal land (the arid and semi-arid areas of sub-Saharan Africa, for example).

The EU can help developing countries to build capacity by promoting international co-operation on this global issue and transferring technology and expertise. In addition to 'North-South' co-operation, 'South-South' collaboration is essential in tackling these issues, and Europe can help create new opportunities for this. Through its Cotonou Agreement and its African, Caribbean and Pacific (ACP) programmes, the Union recognises the need to promote such regional and inter-regional co-operation.

By focusing on current centres of scientific excellence in developing countries – including those with world-class research expertise in the plant sciences, such as Brazil and China – young scientists from other developing countries can be helped to receive expert training in areas critical to the needs of their own nations. Indeed, the training of young scientists from developing countries in such areas as plant breeding and biotechnology is a fundamental requirement for long-term regional (and perhaps global) food security.

Among the specific areas that require focused R&D in developing countries are pest and disease resistance, stress tolerance and ways of increasing valuable micronutrients in the diet. Owing to the value, in terms of breeding potential, of the wild relatives of today's crop plants, there is also a need for gene banks or germplasm collections. However, many developing countries lack the resources to protect their native plant species, and assistance from developed countries will probably be required. Indigenous biodiversity in developing countries also needs to be protected through strong intellectual property agreements. Again, South-South collaboration can help develop the capacity to deal with such issues.

A number of possible deliverables have been identified in the context of the three goals laid out above. These are:

1. **Improve plant productivity and quality**
   - Identify key drivers of plant yield productivity and stability
   - Improve the quality of plant and tree products
   - Climatic changes and plant tolerance to non-biotic factors
2. **Reduce and optimise the environmental impact of agriculture**
   - Develop methods of crop protection with lower environmental impact

- Improve tolerance and resistance to pathogens and other biotic factors
- Improve the interaction of beneficial biotic factors
- Optimise the utilisation of water resources and fertilisers
- Reduce and optimise the environmental impact of feed

3. Enhance biodiversity

- Characterise and maintain biodiversity
- Characterise pathogen and pest biodiversity and how this affects crops
- Characterise the biodiversity of plant and tree genetic resources
- Improve crop and tree biodiversity through the introgression of traits from wild relatives
- Domesticate new crops and trees

To reach these important goals will require the use of novel tools to study plants at various biological and environmental levels. At the same time, genomics could help to boost plant breeding techniques, leading to improved varieties and agricultural practices.

An array of novel technologies has emerged permitting researchers to identify the sources of crop and tree improvements, namely the genes that contribute to the improved productivity and quality of modern crop varieties and the genes that contribute to a better tolerance to stresses, whether biotic or non-biotic, or to a better utilisation of inputs.

These tools may also contribute to the characterisation and management of plant genetic diversity and genetic resources, as well as the improvement of crop and tree biodiversity. A deeper understanding of how the domestication process works is likely to lead to the emergence of new approaches and methods. Besides research in these fields, researchers should develop predictive methods, including modelling and simulation, that would help to forecast the adaptive response of crops and forest trees to unpredictable environmental changes linked to global warming in various geographic regions in Europe.

Goal one: Improve plant productivity and quality

[Ref.: C3.G1]

Sustainable agriculture, forestry and horticulture require a sound balance between reducing the long-term impact of farming on the environment and maintaining its economic viability. Building a more bio-based economy will help to secure food and feed supplies, as well as promote the production of renewable plant-based energy, wood products and new 'green' products.

Plant productivity and quality is an important component of economic viability. This requires a three-pronged approach as identified above.

Deliverable one: Identify key drivers of plant yield productivity and stability

[Ref.: C3.G1.D1]

Yield is a very complex trait which depends on a variety of limiting factors. In order to improve yield, it will be necessary to identify and describe these key limiting factors through a holistic approach which combines physiological and molecular methodologies.

Metabolic processes affecting productivity should be explored. These include the efficiency of carbon fixation in C4 versus C3 metabolism pathways in plants, metabolite partitioning into cells, their translocation and the accumulation of storage compounds in harvested tissues. A very important aspect of the analysis of the key drivers of plant yield is the study of factors that determine plant architecture (tillering, spikelet numbers, ear fertility, etc.) and development (flowering time).

Sophisticated experimental approaches can now be exploited to study these processes. Metabolomic approaches and mass spectrometry-based analytical methods can be used. On this basis, the modelling of growth processes and of the accumulation of storage compounds in sink tissues will be possible and will facilitate the identification of the key drivers of plant productivity.

Agri-technical approaches, environmental factors – such as sowing density, nutrient and water availability – and climatic factors, all affecting yield, should be investigated. One main challenge would be to tackle the complex interplay between genotype and the environment. From this respect, the recent carbon dioxide accumulation in the atmosphere may require a re-optimisation of the carbon metabolism of plants and tree that evolved for millennia on lower carbon dioxide regimes. Growth chamber experiments, performed in parallel with field experiments, should help to identify the factors which can contribute to regular yields in different climatic situations. New crop management tools integrating the genotype-environment interactions can, then, be provided to farmers, together with the new elite or hybrid varieties issued from these new approaches.

Combining improved photosynthesis and carbon dioxide fixation with nutrient and water use efficiency to obtain elite cultivars [Ref.: C3.G1.D1.S1]

Crops can be compared to factories in which different resources are combined to deliver different classes of products. To optimise performance and maximise yields, all input factors have to be investigated. There are, for instance, important links between carbon fixation, water transport and nutrient utilisation. Ways of improving the use of water can be found in the section on abiotic stress tolerance. Nutrient utilisation efficiency is covered under goal two (deliverable 4).

Photosynthesis is the primary source of energy for the 'plant factory', and it should not be taken for granted that it is used optimally, especially in crops which are grown far from their area of origin. An important input factor necessary for primary biomass production is carbon dioxide fixation. Plants have developed specific mechanisms to improve net CO_2 fixation, such as C4 and crassulacean acid metabolism (CAM). The basic cellular processes involved in the transport of metabolites from source to sink tissues also need to be studied. A detailed molecular understanding of these systems and the detection of relatively simple structured variants could result in promising strategies for incorporating such mechanism in other crop plants with less efficient C fixation or less efficient metabolite production and translocation.

Time frame

Five years:
- Molecular analysis of C metabolism and of N-C nutritional relationships in different crops and trees, the signalling processes involved and the improvement of key coupling factors
- Evaluation of the consequences of carbon dioxide accumulation in the atmosphere on photosynthesis

Ten years:
- Molecular identification of the bottlenecks in basal metabolism (synthesis, transport and storage) in different crops and trees, as well as the identification of performing alleles at different carbon dioxide regimes

Twenty years:
- Production of new cultivars combining efficient photosynthesis and water and nutrient utilisation

Improving plant and tree architecture and developmental characteristics for better yields [Ref.: C3.G1.D1.S2]

Plant architecture and developmental characteristics play a critical role in crop performance. Some gene alleles may have a tremendous impact on the possibility to move from a wild species to a crop. For example, the so-called 'Tb1' locus (gene position on a chromosome) played a key role in maize domestication, as the so-called 'green revolution' Rht locus did for wheat. This illustrates how specific alleles are crucial to the process of breeding high-

yield crop plants. The diversity of harvested tissues (fruit, seed, tuber, root or whole plants), the diversity of day-night regimes affecting bolting, as well as the choice of crop production systems (winter versus spring varieties) lead to different breeding strategies, integrating architectural, as well as developmental, features specific to each crop.

Plant and tree architecture (involving organ size, organ number, spatial distribution, etc) is one of the first plant characteristics which is affected by environmental conditions. In turn, it is a major determinant of whole plant photosynthesis and transpiration (via leaf area) and uptake (via root system). Pathways and genes involved in these changes begin to be identified. Optimisation of the response of plant and tree architecture to environmental conditions required an integrated approach involving 3-D modelling of virtual plants and their responses to the environment, which can capture the genetic variability and simulate its consequences for plant performance.

Another complex and poorly understood factor, the efficiency of metabolite translocation into the 'sink' tissues to be harvested, deserves specific analysis, this process being linked to architectural features. An analysis of sink properties should be performed for major types of sinks (fruit, monocot and dicot seed, wood-forming tissue, tubers and storage roots) to identify mechanisms controlling these processes and ways of optimising them. This will require a crop-by-crop approach, exploiting, when possible, comparative genomics to speed up the discovery of the genes involved and specific performing alleles, as well as their contribution to hybrid vigour.

Time frame

Five years:
- Analysis of the impact of plant architecture and developmental features on yields in different crops and trees

Ten years:
- Molecular identification of performing alleles at critical loci affecting yields in different crops
- Analysis of the basis of hybrid vigour

Twenty years:
- Production of new cultivars combining optimised developmental features with efficient basal metabolism and source to sink translocation processes

Analysis and improvement of factors contributing to growth and yield stability [Ref.: C3.G1.D1.S3]

In the long term, yield stability is a trait which has important economic consequences, since poor or excessive harvests can lead to a destabilisation of markets and compromise farmers income, as well as cause localised food shortages. Climatic fluctuations can impair a variety of processes, such as rooting, fertilisation and grain filling, with important consequences for growth and yields. Breeding strategies can reduce the impact of a changing environment. For instance, hybrids are generally less susceptible to environmental fluctuations than their parents. Each crop has its specific weak points and this sub-deliverable proposes remedial strategies for some of these weaknesses. It complements deliverable three.

Time frame

Five years:
- Analysis of the impact of environmental factors on growth and yield stability in different crops and trees
- Analysis of factors contributing to hybrid vigour

Ten years:
- Molecular identification of performing alleles at critical loci affecting yield stability and wood production in different crops and trees
- Development of breeding strategies optimising yield stability
- Identification and characterisation of genes responsible for meristem performance in different tree species

Twenty years:
- Production of new cultivars combining optimised developmental features with efficient basal metabolism and stable performances in a fluctuating environment.
- Development of new forest reproductive material with high plasticity and improved yield in a fluctuating environment adapted to different management regimes in Europe

Deliverable two: Improve the quality of plant and tree products [Ref.: C3.G1.D2]

Although consumers are concerned about quality issues, the improvement of the quality of harvested plant products has not received, in the past, as much priority as it deserved. Meeting the different quality requirements of the food-feed and non-food industries is an essential component of sustainable agriculture. Therefore, it is necessary to increase our knowledge of key factors affecting the composition and quality of proteins, oils, carbohydrates and fibres. The amino acid composition of proteins, the chain length and degree of saturation of fatty acids within plant oils, the branching characteristics of starch are all typical examples of this feature. Wood quality is another trait involving numerous components. Each of these components can be optimised for different applications, such as polyunsaturated long chain fatty acids for healthier diets, unified starch composition for industrial use and wood for insulation.

The starting point of quality improvement is the development of analytical tools for the monitoring of each plant product quality. The physiological and molecular analysis of biosynthesis, transport and deposition processes, including new sophisticated methods for non-invasive, *in planta* study of these processes can provide the set of information required to identify how, when and where different macromolecules and metabolites are produced and stored, and provide the rationale to improve quality. As the environment has a major influence on the composition and quality of storage material, field trial experiments should be performed to relate quality issues to environmental factors.

Bioinformatics and modelling should help to build a deeper understanding of these processes and their interplays, and define new and targeted strategies to identify and overcome metabolic bottlenecks. Novel approaches should help to define the genetic components involved and to seek improvements, either via superior alleles within given plant materials, or targeted improvements employing biotechnological approaches. To perform these studies, the whole spectrum of functional genomics – candidate gene approaches, gene sequencing and metabolic engineering – could be employed.

Improve the composition of harvested products in major storage compounds [Ref.: C3.G1.D2.S1]

Food derived from plants needs to be improved with respect to its general composition which is not optimal for consumption by mammals, including human beings. Plant proteins are generally poor in specific amino acids, such as lysine and methionin. Plant lipids often contain too high a proportion of saturated fatty acids. For a number of forage crops, digestibility is an important issue. Starch composition should be optimised depending on the planned use. Furthermore, limitations in the quality of available food and feed are also linked to the type of crops which can be grown in the EU. Europe needs to improve this if we are to secure food and feed autonomy in Europe.

This sub-deliverable seeks to tackle major quality issues in the main crops and tree species grown in the EU. This will require a better understanding of basic mechanisms of accumulation of major storage compounds which are under the control of specific regulatory processes.

There are many examples showing that major modifications to seed lipid or amino acid composition are antagonised by degradation processes safeguarding the global composition of the seed. A better understanding of the processes controlling the accumulation of stored compounds is an important prerequisite to the improvement of the global composition of plant products. As for yield issues, the availability of '-omics' tools will help to improve quality through the development of molecular breeding approaches.

Time frame

Five years:
- Analysis of pathways controlling the accumulation of storage compounds and fibre polymers in different crops and trees
- Identification of the steps to be modified for the improvement of global composition

Ten years:
- Improvement of global composition through molecular breeding and/or transgenic approaches in different crops and trees

Twenty years:
- Production of new cultivars combining high yields and improved global composition and quality

Improve the quality of harvested products as starting points for the production of healthy food and feed [Ref.: C3.G1.D2.S2]

Specific aspects of plant metabolism deserve targeted investigation. Such nutrients as vitamins and specific classes of unsaturated lipids, macromolecules (including fibres and antioxidants), mineral nutrients (such as iron or magnesium), and a variety of secondary metabolites are known, or at least presumed, to have an impact on human health. Fruit production raises a number of specific issues as regards quality and taste improvement, often conflicting with shelf life issues. This sub-deliverable targets molecular breeding strategies so as to improve further these different components of food and fruit quality. It seeks to pool efforts around specific quality issues. Comparative genomics should help to improve different crops for similar objectives.

Time frame

Five years:
- Analysis of pathways controlling the accumulation of specific metabolites/macromolecules in different crops and contributing to their quality
- Identification of the steps to be modified for the improvement of composition
- Analysis of specific factors contributing to fruit quality and taste and the development of strategies for their improvement

Ten years:
- Improvement of composition and quality through molecular breeding and/or transgenic approaches in different crops

Twenty years:
- Production of new varieties with high quality and good taste

Reduce the negative impact of factors deleterious to quality [Ref.: C3.G1.D2.S3]

Numerous factors have a negative impact on the quality of food and feed derived from crops. Among them are plant inhibitors which evolved to protect plants from predators. Many plant compounds can be destroyed using simple procedures, such as cooking. However, some of these inhibitors are resistant to standard food preparation procedures and need to be eliminated without compromising other aspects of crop physiology. Among them are compounds preventing digestibility (such as alkaloids or cyanogenic compounds), processing (lignins in paper production) molecules with undesirable environmental effects (including phytin), or simply compromising taste or smell. Molecular breeding approaches, tilling techniques and transgenic technologies, can all contribute to the improvement of crop quality by eliminating these deleterious factors. A second class of factors is toxins produced by plant pathogens. Although another deliverable addresses pathogen resistance, approaches to destroying these toxins by the crop itself should not be disregarded. Finally, in specific polluted areas, the accumulation of heavy metals or other natural toxic compounds (such as arsenic) in crops may compromise their utilisation.

Time frame

Five years:
- Analysis of processes leading to the accumulation of deleterious factors
- Identification of steps to be modified for the improvement of composition

Ten years:
- Improving quality through molecular breeding, tilling and/or transgenic approaches in different crops

Twenty years:
- Production of new varieties with improved quality and taste

Reducing the mycotoxin contamination of crops of significant economic value [Ref.: C3.G1.D2.S4]

The problem of mycotoxin contamination of cereal grains is a major issue in southern European countries with forecasted difficulties in meeting the relevant European regulation standards. Plant breeding would contribute to addressing this issue efficiently. Molecular breeding approaches, tilling techniques and transgenic technologies can all contribute, by creating Fusarium-resistant/tolerant plants, to the improvement of crop quality. Comparative genomics should help to improve different crops for similar objectives.

Time frame

Five years:
- Identification of the source of Fusarium resistance/tolerance in the plant varieties of major crops, especially cereals
- Improving quality through molecular breeding, tilling and/or transgenic approaches in different crops

Ten years:
- Production of new varieties with improved quality and taste.

Deliverable three: Climatic changes and plant tolerance to non-biotic factors [Ref.: C3.G1.D3]

Adverse environmental conditions are major factors directly reducing yield or, at least, impairing plant performance. Global warming, inducing long-term changes to the climate, will have an increasing impact on the cultivation of many crops. Reduced rainfall and increased water requirements will affect crop yields and tree growth. Plants able to withstand drought, cold and salt stress would not only stabilise yield potentials but also contribute to reducing the impact of agriculture on the environment. For example, drought-tolerant crops will require less water for their production and this will lead to reduced erosion and soil salination.

These adverse environmental conditions also increase susceptibility to pests and pathogens, resulting in higher consumption of agri-chemicals and further yield and quality losses. This means that there are direct and indirect benefits to improving tolerance to abiotic factors, particularly in developing countries where more marginal land is farmed.

Forest and plantation trees need special attention because their long life span requires adaptability to abiotic changes during their lifetime. In particular, expected climate change may adversely affect the forest population and tree plantations.

This deliverable addresses tolerance to abiotic factors as crucial to improving agri- and silvicultural sustainability. Tools should be developed to monitor, in real time, the physiological status of a crop subjected to abiotic stresses. An in-depth molecular analysis of the complex processes involved in tolerance to abiotic factors would be required. Models taking into account the parameters crucial for crop and tree tolerance should be constructed. On this basis, stress tolerance would be improved by exploiting genetic variability, either via advanced breeding using QTL analyses and association mapping, or through transgenic approaches exploiting the identified critical factors contributing to stress tolerance.

Improve tolerance to water limitation and drought [Ref.: C3.G1.D3.S1]

Among other abiotic stresses, water supply is the single most limiting factor in many countries, including Mediterranean areas in Europe. Water stress is one of the main factors affecting both plant productivity and regularity. Not only the lack of water but also short periods without rain may affect yield and, hence, quality dramatically. This means that we need to improve the water performance of the plants of tomorrow: water consumption efficiency and tolerance to water shortages. More efficient irrigation management is part and parcel of this process.

To maintain their integrity, plants are able to adapt to the variable environment at different organisational levels. Stomata play an essential role, together with the adaptive changes in plant architecture, such as leaf and root growths, control of branching, or the cellular deposition of waxes. These processes are under study in many laboratories, but their complexity remains a challenge and will require further investigation to identify targets for improvement. However, (i) improving responses, such as the reproductive development of maize or vegetative growth in several species has brought appreciable progresses, (ii) water use efficiency has been improved in several species.

In addition, accurate phenotyping is the most important prerequisite for successful MAS and mapping of the heritable traits of drought tolerance. When complex, low heritable traits are to be mapped, collaboration with experienced plant breeders and crop physiologists is essential. Acquisition of reliable plant, soil or nutrition medium data, in collaboration with relevant experts, is a prerequisite for an accurate interpretation of the experimental results.

Time frame

Five years:
- Analysis of drought tolerance processes
- Improvement of tolerance to water shortages through molecular breeding and/or transgenic approaches in different crops and ornamental plants
- Establishment of a protocol to study the adaptation to water deprivation for different plant phenophases

Ten years:
- Production of new varieties cumulating improved drought tolerance and high yield and quality potential

Improve tolerance to cold temperatures and frost [Ref.: C3.G1.D3.S2]

Frost tolerance is a highly inducible process determined by several genes and to achieve full genetic potential in this area, plants must have time to adapt (become hardened, or acclimatised) at low temperatures. The capability of the plants to cold harden is developmentally controlled, highly depends on the genetic systems influencing the time of flowering (vernalization and photoperiod response genes, developmental rate genes).

Due to the complexity of the adaptation process leading to frost tolerance, the location of the genes mediating the stress response and the adaptation network can be achieved only by exploiting precise genetic stocks and standardised, repeatable experiments (plant growth, stress conditions, etc.).

Researchers should elucidate the genetic/physiological bases of how plants acclimatise to the cold. These methods, in combination with the 'candidate' gene approach which is based on the utilisation of the results derived from the model plant systems, will lead eventually to the better understanding of tolerance to freezing.

Time frame

Five years:
- Analysis of cold adaptation and tolerance processes

Ten years:
- Improvement of tolerance via molecular breeding and/or transgenic approaches in different crops and ornamental plants

Twenty years
- New winter varieties integrating cold tolerance and high yields

Improve salt tolerance [Ref.: C3.G1.D3.S3]
Salt accumulation in soil is a growing concern in many countries. It is often a consequence of intensive/excessive irrigation and non-sustainable farming practices. More salt tolerant plants are needed to bring salinated land back under the plough. However, this should not encourage farming practices leading to higher salt concentrations. Alternatively, salt tolerance would be desirable if it allowed farmers in countries with limited fresh water supplies to irrigate crops using partially desalinated seawater.

Time frame

Five years:
- Analysis of salt tolerance processes

Ten years:
- Improvement of salt tolerance via molecular breeding and/or transgenic approaches

Twenty years:
- New sustainable farming practices based on the utilisation of salt tolerant crops

Adapt forests to climate change: characterise and improve the tolerance of tree species to abiotic conditions [Ref.: C3.G1.D3.S4]
Forest regeneration and the creation of tree plantations require knowledge about the tolerance of the selected provenances or tree cultivars to the given abiotic conditions, as well as their adaptability to expected changes to the climate. The most valuable tree species are widely spread over Europe and beyond, and an adaptation to regional climate conditions, potentially modified by climatic changes can be expected. This work package aims to characterise the regional and geographical variation of tree species according to their tolerance to abiotic conditions and their ability to adapt to changing climatic conditions. Furthermore, the molecular basis of this tolerance and adaptability should be investigated and marker-assisted breeding programmes implemented.

Time frame

Five years:
- Trials with different provenance to investigate the genetic control of tolerance against various abiotic conditions
- Understanding the molecular basis of tolerance and adaptability to various abiotic conditions

Ten years:
- Initiate a marker-assisted breeding programme

Twenty years:
- Transfer new breeding products into forest practice and plantation forestry

Goal two: Reduce and optimise the environmental impact of agriculture

[Ref.: C3.G2]

Agriculture has a variety of impacts on the environment. The countryside that is so familiar to us has been shaped by centuries of farming. The beautiful geometry of yellow rapeseed, green sugar beet, and straw-coloured wheat fields that we can see from aeroplanes is part of our natural landscape. Most of the oak and beech forests that we are proud of in Europe are managed by forestry practices which progressively emerged over the centuries to fulfil our needs for heating and building. That said, agriculture does not always have a positive impact on the environment. Overgrazing was already a problem in the Neolithic period in the Fertile Crescent. The need for charcoal for metallurgy led the Roman Empire to deforest the Mediterranean. Nowadays, in some countries, an excessive use of pesticides and fertilisers may compromise the quality of water resources. Irrigation, which is needed to secure the regularity of production, may deplete rivers and compromise wildlife. Orchard fruit production sometimes requires up to 15 successive phytochemical treatments to control pathogen and pest proliferation, and copper sulphate used as a fungicide accumulates in the soil of vineyards at toxic levels.

While keeping in mind the needs of agriculture to produce enough food, feed and renewable raw material, a major goal for meeting the challenge of sustainability will be to minimise the negative impacts of agriculture on the environment, and to promote its beneficial effects.

Plant genetic improvement could result in new opportunities for adapting agricultural practices used for plant nutrition and plant protection and combining improved efficiency with lower negative impact on the environment. The detrimental effects of chemical crop protection can be drastically reduced as plant breeders succeed in further improving the plants' own abilities to cope with pathogens, pests and other biotic factors affecting their health and productivity. Complete new avenues of opportunities will open as we expand our knowledge of beneficial biotic factor interactions.

Deliverable one: Develop methods of crop protection with lower environmental impact

[Ref.: C3.G2.D1]

Plant protection and agri-chemical weeding has contributed, year after year, to the increase in productivity of crops and there is little chance that we will be able to do without them in the foreseeable future. However, there is an urgent need to reduce the negative impacts of these chemicals, and especially those which are hazardous to humans and the environment. New molecules, with improved toxicity profiles and used in limited quantities, have already brought better solutions and more progress is likely to occur in the future. Nevertheless, their utilisation may vary from country to country and toxicity standards may also differ, even within the Union. Similar standards should be implemented at least among EU Member States and, if possible, internationally.

The assessment of the environmental effects of these agri-chemical molecules needs to be improved, while keeping in mind that an adequate balance between benefits and risks has to be struck. This should utilise improved methods to monitor the performance and persistence of chemicals in the field. Additionally, this should be supported by real-time monitoring of epidemic events so as to optimise the use of phytoprotectants.

Extensive knowledge of the plants metabolic network resulting from the genomics and functional genomics approaches will also be useful to exploit new pathways for plant tolerance to herbicides and fungicides. In addition, this can serve to identify targets for new specialised plant protection agents with minimal environmental impact, using emerging chemical genomics approaches. All these approaches should be supported by better and more detailed molecular modelling systems.

A completely different and new approach would be to develop biofilms to protect plants against disease. Again, molecular biology, genomics and bioinformatics should help to focus and speed up the necessary R&D process.

Perform a systematic and well-balanced assessment of the environmental effects of agri-chemicals [Ref.: C3.G2.D1.S1]

Although strict regulations control the commercialisation of agri-chemicals, the evaluation of their environmental impact often needs further assessment as illustrated recently by the controversies surrounding the effects of Regent and Gaucho on honeybees.

An in-depth, science-based and well-balanced evaluation of the ecological impact of a phytochemical treatment is required to identify its possible harmful effects on components of the field ecosystem and on the countryside in a broader sense. EFSA has recently supported the homologation of Fipronil [Regent active molecule] for seed treatment after a risk assessment. A sound scientific evaluation, taking into account available information, is also required to validate new uses of existing molecules. Different crop protection practices should be compared, including their impact on food and feed quality, to identify, among other things, recommended practices for specific crops.

Time frame

Five years:
- Setting up of monitoring tools for the half life of phytochemicals and their breakdown products in plant and in the environment

Ten years:
- Assessment of the effects of these molecules on the field ecosystem

Twenty years:
- Recommended agricultural practices

Real-time monitoring of epidemic events [Ref.: C3.G2.D1.S2]

Protective management of diseases can lead to the overuse of agri-chemicals. This is especially the case when diseases are not properly identified in due time. However, the diversity of pathogens and their uneven spread are a challenge to a farmer's capacity to identify them. Inexpensive tools allowing an accurate monitoring of diseases are urgently needed to help the farmer to take decisions. These monitoring tools will be the starting point to improving the management of agri-chemicals or developing alternative protection strategies, if they are reliable. This ought to lead to a reduced release of agri-chemicals in the environment.

Time frame

Five years:
- Setting up disease-monitoring tools (biochip-based, etc.)

Ten years:
- Modelling disease spread using monitoring tools

Twenty years:
- Developing decision-support tools

Development of environmentally friendly alternative practices for crop protection [Ref.: C3.G2.D1.S3]

Delivering the protective agent to the crop rather than to its environment is highly desirable. New technologies have emerged which allow adequate crop protection and reduce the amount of agri-chemicals significantly. They achieve this through a variety of techniques, such as coating seeds with the chemical instead of conventional spreading. More generally, there is a potential to develop biofilms to protect plants against pests and diseases.

Alternative approaches relate to land management. It has been known for a long time that agricultural practices have a strong impact on the spread of disease. Crop rotation can be optimised to clean the field of specific pathogens. At the same time, the impact of new farming practices on pathogen spread needs to be assessed. A whole area of research in the field of agronomy needs to be developed to integrate technological progress and appropriate land management.

Time frame

Five years:
- Development of crop-targeted methods of delivery of protective agents
- Evaluation of the impact of different agricultural practices on pest and pathogen control

Ten years:
- Validation of new strategies for the protection of specific crops

Twenty years:
- Optimised, pluri-annual farming practices

Identifying new, environmentally friendly weeding tools and practices [Ref.: C3.G2.D1.S4]

Farming practices have a significant impact on weed proliferation, sometimes leading to major problems for specific crops, such as sugar beet. If not properly managed, the practice of fallowing land can have strongly deleterious impacts on weed control in surrounding areas. At the same time, the list of herbicides suitable for weed control is decreasing.

There is a need to discover new, environmentally friendlier and cost-effective herbicides. The combined approaches of genomics and metabolomics can help to identify essential biosynthetic pathways specific to the plant kingdom from which chemical genomics approaches can lead to the identification of new classes of molecules.

Time frame

Five years:
- Evaluation of the impact of different agricultural practices on weed control.
- Identification of putative targets for new herbicides

Ten years:
- Validation of new strategies for the farming of specific crops

Twenty years:
- New environmentally friendly herbicides

Deliverable two: Improve tolerance and resistance to pathogens and other biotic factors [Ref.: C3.G2.D2]

Pathogens and other biotic factors, such as pests, are major contributors to yield losses in crop plants (including cereals, vegetable, fruit), as well as forest tree and ornamental species. Some also have an important impact on quality due to the production of toxins. As a consequence, one of the major uses of agri-chemicals is to protect crops against pathogens and pests. An obvious alternative to chemical protection is the exploitation of naturally occurring resistance mechanisms.

The identification of plant defence or resistance genes is very likely to benefit from the understanding of the identification of virulence and pathogenicity determinants of pathogens and pests. In particular, major advances can be expected from the understanding of the ways in which pathogens manipulate the physiological processes of their host plants to shut off defence reactions and to turn the plant into a suitable ecological niche.

Further breeding efforts will be needed to pile up resistance and, thus, provide a comprehensive set of resistances to the plant. The breeding efforts can be supported by molecular methods, such as QTL analyses, marker-assisted breeding and genomic tools.

Identification and analysis of genes contributing to pathogen and pest resistances in crops, forest tree species and in related wild plant species [Ref.: C3.G2.D2.S1]

This work package aims to enhance understanding of potential resistance mechanisms, the underlying cellular and metabolic processes and the genes which confer resistance. Crops and trees are also naturally resistant to a number of pathogens and pests, and knowing how this immunity occurs would pave the way to designing strategies for genetic resistance to other diseases. Improving the resistance of crop plants may also require the identification of genetic resources in wild relatives, or even in distantly related species, if the biodiversity of the crop itself is not exploitable for this purpose. Again, genome sequencing and genomic tools would help with the molecu-

lar identification of resistance genes before their transfer into crops is carried out.

Time frame

Five years:

- Inventory of genes contributing to host and non-host disease resistance in subject and other plant species

Ten years:

- Introgression of genes contributing to host and non-host disease resistance
- Introgression of resistance genes via sexual crossings when possible, or genetic engineering when not possible through conventional breeding

Twenty years:

- Piling up multiple resistance in major crops in order to release varieties requiring little or no agri-chemicals for their production

Management of genes contributing to pathogen and pest resistance in the field [Ref.: C3.G2.D2.S2]

Durable resistance requires proper management of resistance genes in the field and the monitoring of the spread of new virulent pathogens overcoming the genetic barriers of resistance. These issues are considered in the biodiversity goal.

Time frame

Five years:

- Determination of crop management techniques which avoid resistance/tolerance from a single gene

Ten years:

- Introgression of new set of resistance genes via sexual crossings when possible, or genetic engineering when not possible through conventional breeding

Twenty years:

- Piling up multiple resistance in major crops in order to release varieties requiring little or no agri-chemicals for their production

Deliverable three: Improve the interaction of beneficial biotic factors [Ref.: C3.G2.D3]

Crop plants in the field are part of a complex network of biotic interactions. A better understanding of all the parts, partners and interactions of ecosystems for forestry and agriculture will be useful in two directions.

On the one hand, they can help to stabilise or even improve the complexity of the affected ecosystems and so stabilise, or even boost, the corresponding biodiversity. On the other hand, biotic interactions can also positively influence the crop plants themselves. Symbiotic micro-organisms in the rhizosphere are the most prominent example.
One of the milestones in this respect would be an inventory of beneficial micro-organisms and the analysis of their impact on crop production and protection against pathogens. A number of plant species release a diversity of molecules in the soil. Some of these molecules contribute to the plants' successful proliferation in the environment and the elimination of competing plant species. This opens up new avenues of crop management which use fewer herbicides.

Among the released molecules are also phytoprotectants acting, for instance, against nematodes, or attractors of beneficial living organisms. A tremendous complexity of interactions, which scientists are just beginning to explore, is at work. When favourable, they will be in a position to exploit these interactions, provided we identify and understand them. Performing an exhaustive inventory of these molecules requires the use of metabolomic tools. Following this, functional genomics approaches will be needed to measure the role and environmental consequences of these identified molecules. Once molecules playing a specific role in the ecosystem have been identified, new strategies for biological control will be established and exploited in crop protection, leading to improved agricultural practices.

Again, bioinformatics would serve to combine all available data and, thus, open new opportunities for comparison, detecting interdependences and developing models to explain these complex networks. It would also support the optimal design of new agricultural practices.

Inventory of beneficialsymbiotic micro-organisms in the rhizosphere [Ref.: C3.G2.D3.S1]

Numerous micro-organisms contribute to the rhizosphere and some are also beneficial to the crop. This includes N-fixing rhizobia, but also mycorhiza and other micro-organisms which act as crop protecting agents against root pathogens. In addition to plant symbiosis and pathogen antagonisms, many soil microbes offer various beneficial functions for the growth of plants and trees.
This may include plant growth promotion, plant elicitation, nutrient acquisition and competition for pathogens. The potential of the micro-organisms is hindered by the huge diversity of soil microbes and its exploitation requires the development of adapted genetic tools of investigation.

Time frame

Five years:

- Develop molecular tools for the analysis of soil microbial functional diversity

Ten years:

- Identify beneficial organisms and the mechanisms of plant-microbe interaction
- Experimentally control beneficial non-symbiotic soil microbes, including microbial antagonists or competitors of pathogens

Twenty years:

- Propose strategies for monitoring soil-borne pests and beneficial micro-organisms through ecological engineering techniques

Inventory and exploitation of molecules released by plants and trees and which play a role in their fitness in the environment [Ref.: C3.G2.D3.S2]

Plants synthesise and excrete a diversity of molecules involved in protecting them against pathogens and pests, as well as the attraction and colonisation of beneficial micro-organisms and insects, and the protection of their habitat against the invasion of other plant species. A number of the molecules and macromolecules can potentially be incorporated into new biotechnologies to improve farming practices.

Time frame

Five years:

- Inventory of bioactive metabolites and their role

Ten years:

- Continuation of the inventory and the development of biotechnologies in the field of crop protection and weed control

Twenty years:

- Integration into farming practices

Development of biological control strategies [Ref.: C3.G2.D3.S3]

A number of living organisms are natural predators preying on pests which they colonise or use as food. These organisms are very diverse, but their exploitation for crop protection in the field needs improvement so that they can be managed efficiently, without creating secondary undesirable effects in the field ecosystem.

Time frame

Five years:

- Inventory of organisms of interest to biological control issues, and analysis of their mechanisms of action

Ten years:

- Development of biotechnologies based on these organisms or the set of genes that play a central role in their effectiveness
- Exploitation in the field of crop protection and weed control

Twenty years:

- Integration into farming practices

Deliverable four: Optimise the utilisation of water resources and fertilisers [Ref.: C3.G2.D4]

Alongside the nutrients needed for healthy plants growth, water availability is a crucial factor in crop production. Additionally, the excessive use of fertilisers, encouraged by the race for higher yields, has compromised the quality of water resources, in some case.

Plant genomics can help to provide tools to develop plant varieties capable of using water more efficiently. It can also help to increase the nutrient utilisation efficiency of crops. A nutrient of major interest is nitrogen. This element is needed in relatively large amounts, as it is an essential component of all proteins and nucleic acids. As agricultural soils are progressively depleted of their nitrogen due to continuous uptake by crop plants, N fertilisation is required to maintain crop production. The nitrogen present in the air cannot be directly utilised by most plants and crops. However, legumes have developed specific symbiotic systems with micro-organisms able to fix nitrogen from the air. Although much work has been done in the past on legumes, our knowledge is still not sufficient to transfer this N-fixing ability to other crops due to the complexity of the process and the number of genes involved.

Succeeding in this would reduce the need for mineral fertilisers and, thus, safeguard yields and reduce effort in both economic and ecological terms. Until this happens, we need to concentrate on a more effective use of nitrogen, mainly nitrate, which is universally used by plants, including nitrogen-fixing plants, and to a lesser extent other forms of nitrogen (ammonium, urea, etc.) also used as fertilisers.

Develop monitoring tools and adapted agricultural practices to reduce and optimise the need for fertiliser and water [Ref.: C3.G2.D4.S1]

To prevent agricultural soils from being progressively depleted of their mineral nutrients due to uptake by crops, fertilisation is required to maintain crop production. Monitoring the nutrient status in the field and in the crop helps to provide adapted amounts of fertilisers in due time. Monitoring tools do exist, but they could be improved to provide 'online' information which is directly exploitable for the delivery of fertilisers and water. Plants have different strategies to collect, store and recycle mineral nutrients, and this has an impact on the steps at which the delivery of different nutrients has to be performed. This also holds true for water utilisation.
The type of nutrients delivered also affects soil retention, uptake by the root system and translocation to the sink tissues where the nutrients are required.

Another layer of complexity resides in the analysis of the competition between crops and weeds for these limited resources. On the basis of this knowledge and by developing new delivery technologies, new strategies of crop fertilisation and management can be optimised so that plants selectively receive an optimal amount of water and fertilisers for their proper development, and a minimum amount of these remain unused in the soil.

Time frame

Five years:

- New real-time monitoring tools
- Modelling of uptake, storage and utilisation of water and fertilisers by crops

Ten years:

- Development of new delivery techniques targeted at crops

Twenty years:

- Integration into farming practices

Identification of the limiting steps in nutrient use efficiency and breeding crops for improved nutrient efficiency **[Ref.: C3.G2.D4.S2]**

Many nutrients are essential for plant growth, such as those containing nitrogen and phosphorous. However, such nutrients can have a negative impact on the environment when improperly managed. The uptake efficiency of N-containing fertilisers depends on the crop. The second step of N assimilation can also vary greatly in efficiency, as can the efficiency of the translocation of the N-containing assimilates to the sink tissues, seeds or other tissues. N-utilisation efficiency was not the focus of much breeding in the past, since the negative impact of fertilisers on the environment was not considered. However, genomics and metabolic studies hold the promise of improving N-utilisation efficiency in many crops.

This can be achieved by improving the N-uptake ability of root systems, as well as through improved translocation and assimilation processes. These genetic improvements can be coupled with improved agricultural practices, as seen in Scope 3.2.4.1, leading to a strong reduction in the negative environmental impact of fertilisers. The same kind of argument holds true for other essential minerals with a negative impact on the environment, such as phosphorus, involved in the eutrophication of water resources. The utilisation of other essential nutrients, such as potassium, iron and zinc can also be improved, but this would be done primarily to increase crop production and quality. Functional genomics approaches, bioinformatics tools, and

systems biology models can be combined with molecular breeding approaches and, if needed, with transgenesis to obtain elite cultivars with high potential for nutrient utilisation.

Time frame

Five years:
- Molecular analysis of the basis of nutrient utilisation efficiency in different crops

Ten years:
- Identification of the bottlenecks in nutrient utilisation in different crops

Twenty years:
- Improvement of different crops for nutrient utilisation efficiency via QTL analysis, molecular breeding and transgenesis

Transfering the N-fixing ability of legumes to other crops and trees [Ref.: C3.G2.D4.S3]

Legumes have developed symbiosis with N-fixing bacteria. This process has emerged through co-evolution of plants and soil-living bacteria. It would be desirable to extend this symbiotic process to other crops, especially cereals. For the time being, this is a major challenge. An inventory of the genes contributing to this process is being taken and the analysis of the roles of the proteins for which they code is being performed. Legumes can be improved as regards their N-fixing ability which, for instance, is generally strongly reduced in soils containing reduced nitrogen.

It is also time to try to exploit our knowledge of the symbiotic process occurring in legumes for the building of N-fixing non-legume crops. This will require the use of genetic engineering tools, since a number of the genes involved do not exist in non-fixing crops.

Time frame

Five years:
- Molecular analysis of the basis of symbiotic processes in N-fixing plants

Ten years:
- Identification of the bottlenecks in N fixation and utilisation in N-fixing crops, and their improvement through QTL analysis and breeding

Twenty years:
- Transfer of the N-fixing ability of legumes to non-legume crops, such as cereals

Modelling of crop and forestry systems [Ref.: C3.G2.D4.S4]

The balance between the loss and the use of resources by crops (such as nutrients and water) controls both crop efficiency and environment contaminations by element excess. The balance is driven by the fitting or matching of the availability to the demand of the plant throughout its different developmental stages. New digital modelling of nutrient and water delivery, rhizosphere processes and rooting is a priority in the development of genetic engineering techniques, soil management practices and cropping and forestry systems.

Cultivation practices, such as the choice of a genotype, sowing dates, fertilisation, watering and pest controls interact considerably and their results depend largely on the soil type and the weather patterns of the year in question. As it is impossible to test experimentally all combinations of events, modelling is a useful tool for 'virtual agriculture' testing. Models already exist and are tested on networks of experiments. The development of this approach at the European level will be of considerable benefit both from the scientific and ecological points of view.

Time frame

Five years:
- Develop new mechanistic soil/plant digital models of the use/loss of resources

Ten years:
- Propose new generations of crop models

Twenty years:
- Promote and implement model-based strategies for the management of crop production

Deliverable five: Reduce and optimise the environmental impact of feed [Ref.: C3.G2.D5]

Europe consumes some 400 million tons in raw materials for feedstuff. Thus, both feed production and consumption can have an environmental impact that it is important to minimise. Precision farming can reduce the use of such inputs as fertilisers and pesticides. The use of nitrogen-fixing plants and legumes can greatly decrease the use of nitrogen fertilisers which represent more than 50% of crop energy cost. Increasing the sustainability of grasslands – which make up about 40% of arable land in Europe – is a major objective.

Decreasing inputs in feed crop production [Ref.: C3.G2.D5.S1]

Investigating the epidemiology of pathogens and pests; the influence of agricultural practice (crop rotation and crop management) and of environmental factors on these biotic interactions; the production of diagnostic tools and predictive models for epidemics can lead to improved crop management and precision farming. This would, in turn, result in a reduced dependence on pesticides.

Researching crop physiology and the agronomy of nitrogen, phosphorus, sulphur and other elements; the influence of agricultural practice (crop rotation and crop management) and of environmental factors on element life cycles; the production of diagnostic tools and predictive models for plant nutrition might lead to reductions in the use of fertilisers.

Increasing the use of legume crops [Ref.: C3.G2.D5.S2]

Thanks to symbiotic associations, legumes are able to fix large amounts of nitrogen. This means that they do not require the use of nitrogen fertilisers and their introduction in a crop rotation system allows for a reduction in the use of nitrogen fertiliser. The seed protein content of legume is two to four times higher than in cereals. Presently, legumes are used in about 5% of cultivated areas in Europe, in contrast to 25-30% in the USA. This will not help efforts to curb greenhouse gas emissions, as the production, transportation and use of nitrogen fertilisers consumes vast amounts of fossil fuels.

The European Parliament's Agriculture Committee organised a hearing in Brussels. in 2002. on 'Options to promote the cultivation of plant proteins in the EU'. The rapporteur's conclusions included the following: (1) the EU has to decrease its dependence on imported proteins, (2) protein production must be compatible with the development of sustainable agriculture, and (3) research to encourage the development of legumes has to be supported.

Increasing the sustainability of herbivore farming systems [Ref.: C3.G2.D5.S3]
Grasslands, which represents about 40% of arable land in Europe, can improve the sustainability of farming systems. Specific difficulties encountered with grassland research and management necessitate specific research. Forage crops often have complex genetic systems (polyploidy and allogamy) and both temporary grasslands in rotation and permanent grasslands contain mixtures of species which have to be taken into consideration, especially with regard to animal nutrition.

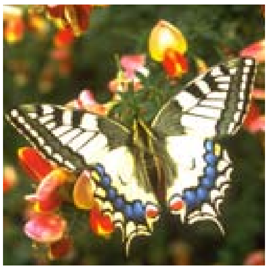
Time frame

The following research activities should be undertaken to tackle the issues covered by the three scopes in deliverable five, goal two, challenge three.
Five years:

- Use comparative genomics (of the genome sequencing of rice and model legumes) to facilitate the genetics of polyploid and allogamous species and breeding of diverse forages.

Ten years:

- Analyse the functioning and dynamics of mixtures of forage species, the influence of environmental factors and of selective grazing by herbivores; construction of predictive models for improved grassland management.



Goal three: Enhance biodiversity

[Ref.: C3.G3]

Worldwide, the human population will continue to grow over the coming 25 years. At the same time, a higher standard of living in emerging economies, such as China, could lead to higher meat consumption. This would spark ever-increasing demand for food, feed and renewable resources, triggering an intensification of agricultural and forestry practices and the farming of more arable land. This would ultimately lead to the erosion of genetic diversity in the field as a consequence of intensifying agricultural practices. It will also reduce the expanse of wild areas and will adversely affect wild species living in these areas. In Europe, many forest and marshland areas have been converted into farmland over the centuries, and this process is continuing owing to the intensification of irrigation practices. In addition, the conversion of agricultural land to forests is taking place in several European countries and the effects of this change have to be taken into consideration.

The impact of human activity on biodiversity in the forestry sector has been much smaller than in agriculture. However, the preferential use of certain, mainly coniferous, species, selected breeding material (such as in Scandinavia), the conversion of traditional utilisation (such as coppice) into more productive high forests, and the extended transfer of forest reproductive material all over Europe has intentionally or unconsciously altered forest biodiversity and genetic resources.

In developed and emerging economies, biodiversity is also being reduced as a consequence of agricultural mechanisation which leads, for instance, to the disappearance of hedges in the countryside, inducing perturbations of rural ecosystems. Another consequence of the intensification of farming practices is the reduction of the biodiversity of crops in the field and of the diversity of foods which are available to the consumer.

In some parts of the developing world, such as in rainforests, there is a wealth of biodiversity that needs to be protected and used for the good of humanity, i.e. to develop medicinal products or new domestic crop varieties. This can be done through strong and fair intellectual property rights agreements. In addition, north-south and south-south collaboration is needed to establish accessible gene banks and germplasm collections.

Since human population growth is unlikely to stop, a realistic approach has to be taken to face these challenges by trying to maintain and increase, if possible, the productivity of more diversified crops and trees, such as deciduous species, without reducing biodiversity.

This requires the development of tools to characterise and monitor biodiversity on farmland, in forests, as well as in the surrounding wild areas. A better knowledge of the biodiversity of pests and pathogens is also needed to develop crop protection strategies. These strategies have to rely on the exploitation of the biodiversity of genetic resources for the improvement of crop tolerance to pests and pathogens.

Deliverable one: Characterise and maintain biodiversity [Ref.: C3.G3.D1]

It is well known that agricultural practices affect the biodiversity of farming ecosystems. Experiments performed over the last century at Rothamsted experimental station (UK) have shown the impact of fertilisation on plant diversity in pastureland. The elimination of hedges has been demonstrated to affect biodiversity, as well as the spread of disease.

However, the impact of insecticides on insect biodiversity in the field is still a matter of controversy. This is mainly because the tools allowing the rational estimate of biodiversity at a global scale are labour-intensive and low-throughput. There is a need to improve these monitoring tools, to model ecosystems and to provide validated agricultural practices which minimise biodiversity loss.

Setting up protocols for biodiversity assessment in representative farming and forestry practices [Ref.: C3.G3.D1.S1]

Evaluating the biodiversity of an ecosystem is not a trivial task. This needs an ecological inventory of visible plants, insects and animals, but also of the soil-living organisms.

If different management practices are compared, such an inventory has to be dynamic and should lead to statistically validated measurements. New techniques based on DNA sequence inventories have potential, especially for micro-organisms which cannot be isolated in pure cultures.

These monitoring tools can be used to compare different agricultural practices (for example, ploughing or herbicide-based cleaning of the soil before sowing, the presence or absence of intensive irrigation, chemical versus genetic crop protection against rust, crop rotation versus fallow practice, or organic versus chemical fertilisation) and different forest management systems. This type of analysis can provide data that is useful for other sub-deliverables.

Time frame

Five years:
- Setting up of monitoring tools

Ten years:
- Analysis of management practices differing by only one major parameter

Twenty years:
- Analysis of different integrated agricultural practices

Model field ecosystems and their relations to surrounding areas [Ref.: C3.G3.D1.S2]

Different agricultural and forestry practices probably affect species biodiversity and gene frequency in a population (for instance, insecticide-resistant esterase). This sub-deliverable plans to model populations of different living organisms, focusing on the various selection pressures in action (for example, the dynamics of weed populations according to crop rotation, their resistance or sensitivity to herbicides, and their susceptibility to grazing animals).

If GMO practice is to be tested, an assessment of gene flow should also be monitored. The objective is also to monitor and develop the effects of different management intensities and practices (including wildlife) and different forest fragmentation patterns on species and ecosystem diversity (including host-pathogen interactions).

The outcome would be models to predict the evolution of biodiversity in the field and in forests as a consequence of a specific agricultural practice.

Time frame

Five years:
- Exploitation of data existing in the literature to build first generation models

Ten years:
- Modelling of biodiversity evolution and genetic drift in simple comparisons

Twenty years:
- Modelling of biodiversity evolution in different integrated agricultural practices

Provide farmers with protocols of good agricultural practices [Ref.: C3.G3.D1.S3]

The goal of this sub-deliverable is to draw conclusions from these different studies and recommend the best agricultural practices.

These recommendations should include an analysis of the consequences of the considered practices in terms of farm and forest management and economic viability, based on different economic scenarios, such as the level of taxpayer support.

Time frame

Five years:
- Selection of a set of agricultural practices expected to have a positive impact on biodiversity

Ten years:
- Socio-economic analysis of these agricultural practices on farming activity

Twenty years:
- Selection of recommended agricultural practices for different types of farming activities

Deliverable two: Characterise pathogen and pest biodiversity and how this affects crops [Ref.: C3.G3.D2]

Protecting plants and trees against pathogen and pest attacks is a major and permanent concern for farmers and forest managers. Perennial species, such as grapevines and apple trees, can receive up to 15 chemical protective treatments in a single season. This has an obvious impact on the biodiversity present in the vineyard/orchard. The dynamics of pathogen spread is affected by a number of factors (genetic homogeneity of the crop, environmental conditions, agricultural practices, etc.). Convincing evidence has been given that the management of genetic resistances in the crop and the strategies of chemical protection can have contrasting impacts on disease aggressiveness and biodiversity.

A better knowledge of the dynamics of pathogen spread should help to devise better agricultural practices and help to protect biodiversity. With the new era of genomics, the access to genome sequences of important pathogens is the first step in the analysis of the biodiversity of these pathogens. Of special interest is the access to virulence and pathogenicity genes which by mutation and recombination can lead to new host specificity in a similar way to that of infectious diseases in mammals.

Collect and exploit existing collections of plant and tree pathogens and pests, and assess their virulence and pathogenicity on crops [Ref.: C3.G3.D2.S1]

Numerous diseases are known to attack plants. Pathogens and pests which have a serious economic impact will be chosen for an in-depth analysis of their biodiversity. This would involve the characterisation of host susceptibility to different species. This analysis should be extended to core collections of wild species related to the crop of interest. It is known that a synergy of biotic and abiotic factors can contribute to the development of diseases, such as corn borer and fungi. An analysis of the biodiversity of pathogens and pests interacting with the same plant should be performed. Molecular techniques should be used to study evolutionary relationships between different races (variations within a specie) of a pathogen.

Time frame

Five years:
- Selection of relevant species (viruses, bacteria, fungi, insects, nematodes, etc.) and inventory of their pathogenicity on representative crop accessions and related wild species in different physiological conditions

Ten years:
- Analysis of race biodiversity using DNA sequence analysis

Twenty years:
- Global analysis of the different pathogens and pests interacting on the same crop and their synergy and interplay with abiotic factors.

Identify virulence and pathogenicity genes [Ref.: C3.G3.D2.S2]

For micro-organisms, molecular techniques should be used to identify pathogenicity and virulence genes. This can be achieved by sequencing a genome of each relevant pathogen, performing comparative genomics studies, developing insertion mutagenesis tools and screening for mutants impaired in pathogenicity and virulence.

Similar approaches should be developed for pests as regards genome sequencing and comparative genomics. Functional analysis of pest genomes should be performed using a combination of transcriptome analysis, chemical mutagenesis and tilling-based identification of the function of genes contributing to the aggressiveness of these pests.

Time frame

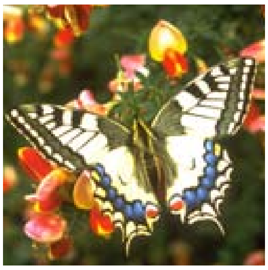
Five years:
- Selection of genomes to be sequenced and their ‘shotgun’ sequencing

Ten years:
- Comparative genomics and the identification of virulence and pathogenicity genes

Twenty years:
- Characterisation of virulence and pathogenicity genes, including their functional analysis

Analyse genetic diversity of pathogens at the molecular level [Ref.: C3.G3.D2.S3]

Once virulence and pathogenicity determi-



nants have been identified, factors affecting their biodiversity and the spreading of new virulent races can be studied. The goal would be to anticipate the occurrence and spread of new races and to devise management strategies reducing the emergence of these new races.

Time frame

Five years:
- Analysis of factors affecting the biodiversity of pathogens

Ten years:
- Identification of the mechanism of generation of new virulence and pathogenicity genes and of new races carrying them

Twenty years:
- New management strategies for crop protection leading to the reduced use of phytochemicals

Deliverable three: Characterise the biodiversity of plant and tree genetic resources [Ref.: C3.G3.D3]

Crops have been progressively domesticated to improve different traits, and favourable alleles at different loci have been piled up in the same genotype to obtain modern varieties. This selection process has generated numerous accessions in which diversity exists that can be explored and possibly exploited to generate new elite varieties. The collections of landraces, hybrids and inbred lines available for this task are maintained in resource centres. There is often some concern over how representative and useful such collections are, as well as the exact origin of many accessions and the existence of possible redundancy.

At the European level, the Ministerial Conferences on the Protection of Forests in Europe (MCPFE) – which were held in Strasbourg (FR), Helsinki (FI), Lisbon (PT) and Vienna (AT) – recommended, in several politically binding resolutions, the conservation of forest biodiversity, including the preservation and sustainable use of their genetic resources. MCPFE is a major component of the European Forest Strategy (EFS) and is also part of the Common Agricultural Policy (CAP). In contrast to agricultural crops, forest tree populations are much less affected by humanity. Tree populations are managed in much longer rotation periods than in agriculture and are more heterogeneous. From an evolutionary perspective, it is understandable that tree species are genetically more diverse than plants with shorter lives. Native forests have faced significant environmental changes in the past and have been subjected to human activity for centuries, although to different degrees across the EU. With the exception of some tree species, such as poplars and certain pines, the vast majority is not, strictly speaking, domesticated. A recent global concern has been climate change which is regarded as one of the major threats to forests. Diversity, both at the species and genetic level, is one of the pivotal points to ensure sustainability in the forestry sector. Since forest reproductive material has been moved extensively in the past, the conservation and characterisation of biodiversity has to be addressed at a European scale.

For most crops and some model tree species, genomic tools based on the analysis of DNA polymorphism are now available to analyse the genetic biodiversity hidden in collections. This deliverable seeks to collect data for each crop on genotypes and phenotypes of all available accessions, to integrate these data into a user-friendly database and to create a core collection maximising the available biodiversity. This would be used as a starting point for further work. In a second step, the biodiversity captured in the core collection would be systematically analysed for linkage disequilibrium between haplotypes and distinctive phenotypic traits. This requires high-throughput and high-density genotyping, as well as precise analysis of various aspects of phenotypes under controlled growth conditions.

For traits of major importance, the genetic determinants of these traits will be further analysed through the creation of RILs between accessions differing for the traits under study and QTL analysis. These approaches should lead to the identification of haplotypes which are exploitable for marker-assisted breeding of elite varieties. Major QTLs can be characterised further by chromosome walking to identify the molecular basis of these traits. This will ultimately lead to the identification of candidate genes underlying the traits of interest. A useful complement to this approach would be the validation of some of these candidate genes using a reverse genetic approach based on the identification of mutations affecting the gene of interest, tilling, or transgenesis/ RNAi approaches.

Core collections established for major crops and trees [Ref.: C3.G3.D3.S1]

Resource centres should play a central role in this sub-deliverable by performing an inventory of the main agronomic traits for each accession collected and expanding the collections where necessary. This includes wild relatives of the domesticated crops, new and under-utilised crop species and trees under study. The genotyping of accessions can be performed once a set of molecular markers, such as microsatellites or SNP, has been chosen so as to cover the genome of interest on a 10-20 cM basis. From this phenotypic and genotypic analysis, core collections will be established and maintained in different environments, permitting the analysis of specific traits.

Time frame

Five years:
- Genotyping of all accessions

Ten years:
- Phenotyping for major agronomic traits and storage of data in user-friendly databases
- Core collections established for all crops

Phenotype analysis of all relevant traits, including biochemical traits [Ref.: C3.G3.D3.S2]

An in-depth analysis of the different facets of the phenotype should be performed on the core collection grown in controlled environments. '-omic' approaches can be exploited to accumulate data on metabolome, proteome, structural polymers, storage compounds, architecture and the response of plants to various environmental constraints (nutrition, as well as biotic and abiotic stresses).

The ability to isolate large quantities of vascular tissue has led to high quality libraries from various tree species that are being used to study not only lignifications but also cell wall synthesis. In addition to these synthetic pathways, adaptive traits, such as bud burst, branchiness and stem form should be studied.

Time frame

Five years:
- Metabolome and storage compounds

Ten years:
- Proteome and complex polymers

Twenty years:
- Response to various environmental constraints

Evolutionary genomics and linkage disequilibrium analysis of biodiversity components [Ref.: C3.G3.D3.S3]

The study of genetic structures and genetic diversity is probably the most important application of genetic markers in population biology and genetic resource management. Natural hybridisation is an important force affecting the evolution and ecology of forest tree populations, since it can result in positive (increased genetic diversity, Darwinian fitness and adaptability) and negative (loss of genetic diversity and outbreeding depression) consequences on the viability of forest tree populations.

Depending on a crop's sexual reproduction strategy (autogamy, allogamy, etc.) and other factors (diploïd versus amphiploïd), the average size of haplotypes varies greatly.
An optimal density of polymorphic markers should be designed to perform linkage disequilibrium analysis in a core collection carefully built to prevent bias in LD analysis. A high throughput procedure by whole genome scan can be performed to detect haplotype links with specific traits. Such links when validated by statistical analysis can be tested through reverse genetic approaches.

Time frame

Five years:
- Coverage of the genome with an optimal number of SNP markers
- Genotyping of the core collection

Ten years:
- Accumulating LD analysis data and producing mutagenised populations for tilling experiments
- Validation of candidate genes for specific traits
- Development of population models

Twenty years:
- New strategies for the management of genetic resources

Creating segregating populations from core collections and mapping agronomic traits through QTL analysis [Ref.: C3.G3.D3.S4]

Once core collections have been created, they can be used to identify the molecular basis of specific agronomic traits. This can be achieved by making appropriate crosses between accessions showing contrasted phenotypes which are as genetically distant as possibly available based on DNA polymorphism analysis. When possible, RILs should be produced by repeated selfings, haplo-diploidisation or other procedures. The segregating material can be genotyped using molecular markers. In parallel, phenotype analysis can be performed in appropriate conditions to study the trait(s) of interest. For instance, nematode resistance assays may require a succession of field trials in specific contaminated soils so as to homogenise the data inherently biased due to the uneven distribution of the nematode in the soil and to the diversity of pedoclimatic conditions affecting the nematode biotope. Only QTLs consistently identified should be characterised further. Specific recombinant genotypes will then be chosen to perform a fine mapping of the main QTLs identified for the trait of interest.

The 'QTL mendelisation' approach, when valid, can be used in the positional cloning of the molecular basis of the QTL under study. This would ultimately lead to the most favourable conditions for the formal identification of the gene of interest and directly provide access to the analysis of its variability and diversity in the subject species. Since taxonomically related crops share similar genetic determinants of their variability, the identification of the molecular support of a QTL will open avenues of research into similar traits in related crops. When the work of mapping of a QTL does not lead to the formal identification of a single gene responsible for the trait, but only to a small chromosomal area encompassing a small list of genes, complementary functional analysis tools will be required to proceed further as illustrated by recent examples in the literature. Ultimately, model species can contribute to the deciphering of the basis of genetic diversity in crops, as already illustrated for the control of flowering time, by providing shortcuts to the identification of genes involved in specific QTLs.

Time frame

Five years:
- Selection of accessions of interest and generation of recombinant materia.
- QTL analysis of traits of interest: including physiological and biochemical traits

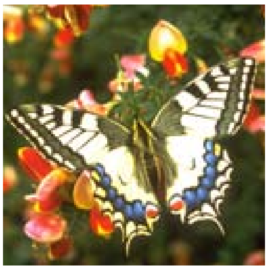
Ten years:
- Continuation of QTL analysis and the generation of populations allowing the refined mapping of QTLs
- Identification of the molecular support of specific traits

Twenty years:
- Exploration of the genetic diversity of alleles at loci identified to be involved in specific QTLs at the level of the families of taxonomically related crops

Deliverable four: Improve crop and tree biodiversity through the introgression of traits from wild relatives [Ref.: C3.G3.D4]

The genetic diversity in crop genomes is surprisingly low. In many species, a bottleneck has been created by a small, or even unique, genotype selection event. For instance, in maize, a single Tb allele is found in most cultivars. Although the breeding process, involving the search for cultivars adapted to extreme environments (compared to the habitat of wild relatives), has convincingly generated new biodiversity in many crops.

There is an obvious need to enlarge the pools of alleles accessible for the breeding of a crop so as to increase its biodiversity and to begin the selection of new varieties combining high quality and hardiness, as well as resistance to a broad range of pathogens. It has been illustrated by Tanksley et al that, at least in tomato, an almost unlimited source of genetic diversity resides in wild relatives, as long as they are interfertile with the crop of interest. But to exploit this biodiversity, several rounds of backcrosses have to be performed to ob-



tain introgressions of a small proportion of the donor genome.

The generation of substitution lines, in which only a chromosome fragment generally smaller than 30 cM, allows the scanning for traits of interest by comparing these substitution lines to the wild type. This approach has the potential to be employed for the breeding of many crops. It requires the genotyping of substitution lines to identify a minimum set of simple substitutions, including the majority of the genome of the donor species, and can be used for the breeding of desirable traits, such as durable resistance to pathogens, higher nutritional quality and reduced need for fertilisers.

Creating advanced back cross populations and sets of substitution lines [Ref.: C3.G3.D4.S1]

Major EU crops should be used for the production of advanced back cross lines with wild relatives. The first step would be a survey of these wild relatives. An analysis of the interesting traits they may carry (for instance, pathogen and pest resistance) should be performed. A study of the viability of hybrids between the crop of interest and the wild relative, as well as the aptitude of hybrids to recombine homeologous chromosomal areas can be performed for each introgression. Embryo rescue may be required to obtain viable hybrids. These plants would then be backcrossed to the crop (AB plants) and their genotype analysed.

The AB plants can be genotyped so as to identify a tiling of introgressed chromosome fragments covering the entire donor genome. These selected introgression lines will be studied for a number of agronomic traits and QTLs identified.

Time frame

Five years:
- Inventory of wild relatives of a crop and analysis of cross fertility

Ten years:
- Generation of AB populations and genotyping
- QTL analysis of introgression lines

Twenty years:
- Analysis of the biodiversity of the identified gene in natural population and the search for even better performing alleles

Introgression of specific loci in elite varieties [Ref.: C3.G3.D4.S2]

The QTLs identified can be transferred before even knowing the underlying gene contributing to them. This can be readily exploited and piled up to create new commercial varieties.

When a molecular identification of the gene involved in the QTL becomes available, an analysis of the variability of the gene in different accessions should be performed, with the goal of identifying new alleles and sources of exploitable biodiversity at the locus.

Time frame

Ten years:
- Introgression of QTL bearing loci in elite varieties

Twenty years:
- Idem for new alleles identified in other wild relatives of the crop on the basis of the cloning of the gene(s) involved in the trait under study

Deliverable five: Domesticate new crops and trees [Ref.: C3.G3.D5]

The international standardisation of farming practices leads to the progressive decline of minor crops, and to a subsequent progressive reduction in biodiversity. However, it is well known that the diversification of food sources is an important aspect of human nutrition. Furthermore, the analysis of plant metabolites has revealed that their diversity often reflects botanical diversity. A minor crop, such as flax, has a seed lipid composition unexpectedly well adapted to providing essential fatty acids for animal and human nutrition.

In his book, *Crops and man*, Jack Harlan listed more than 400 species that were domesticated to some extent. The comparison of these domesticated crops with their wild relatives has shown that, for taxonomically related crops, similar genetic changes have been selected by humans during the domestication process, thus favouring specific aspects of farming practice, such as the simplification of the harvesting process. The molecular identification of these genes opens the way to screening for similar genetic modifications by using reverse genetic approaches to improve the domestication of 'orphan' crops or even wild species of potential interest. One step further would be to screen for a trait of interest, such as the accumulation of a specific molecule, or for a composition well adapted to the nutritional needs of mammals and humans, and to derive rapidly a crop suited to standard farming practices from the identified wild species.

In contrast to crop plants, forest trees are virtually undomesticated. This is a major advantage in conventional forestry, but has drawbacks for plantation forestry. Long generation times and high levels of inter-population gene flow make conventional breeding programmes difficult. However, the identification of QTLs and resistant traits, together with the characterisation of regional and geographical variation of these traits, should permit the future domestication of selected tree species.

This domestication of wild species, or completion of the domestication of ancient crops, would ultimately increase the biodiversity of crops grown in rural areas and the quality of the landscape there.

Evaluating the potential of new crops and trees [Ref.: C3.G3.D5.S1]

New crops can be derived from wild species, as well as from partially domesticated crops. At first, an analysis of the traits of interest and an estimation of their agronomic, nutritional and industrial qualities should be performed. On the basis of a short list of important goals, a phenotypic screening would be performed on a large diversity of species, including 'orphan' crops, such as lupin, of reduced use due to limited domestication or breeding. Their potential for domestication would then be evaluated.

Time frame

Five years:
- Survey of traits of interest

Ten years:
- Screen for these traits and identify the species of interest

Exploit synteny to identify and modify domestication genes [Ref.: C3.G3.D5.S2]

A number of genes have been identified which contribute to various agronomic traits, including seed dormancy, flowering time, apical dominance, fruit formation, synchronisation of seed maturation, shattering, etc. Mutagenised populations can be screened for mutant alleles at the loci of interest. Alternatively, genetic transformation can be used to introduce performing alleles issues from other crops in the species to be domesticated.

Time frame

Ten years:
- Screen for performing alleles by tilling or by genetic transformation

Twenty years:
- Piling up of domestication traits in a common genotype

Perform conventional breeding for yield and agronomic performance [Ref.: C3.G3.D5.S3]

Once the domestication traits have been optimised, conventional breeding can help to fine tune the different traits contributing to an exploitable crop. Agronomic approaches need to be devised to obtain an efficient cropping system. This includes farming practices leading to a control of the propagation of the species in the wild areas surrounding the fields where that crop is produced.

Time frame

Ten years:
- Conventional breeding for yield and various agronomic traits

Twenty years:
- Building of a production scheme, including homogeneous seed stocks, optimised farming, harvesting and processing
- Evaluation of the risks of uncontrolled propagation of the new crop in the environment

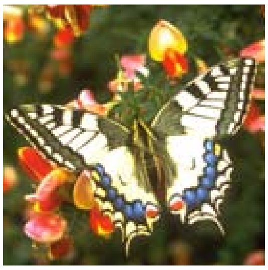
Biodiversity plays a functional role in maintaining the sustainability of forests. Achieving this requires new research methodologies, data processing techniques and interdisciplinary co-operation. New genomic tools are or will be indispensable for the future development of sustainable strategies to utilise and conserve genetic resources. However, to get better insights into the genome of forest trees and its functional role at the ecosystem level, new methods for monitoring and predicting the evolution of the adaptive diversity of forest trees should be developed. Furthermore, research competitiveness in ecological genetics needs to be enhanced through the integration of various biological and spatial scales. Management methodologies for implementing research results into forestry would also be necessary. This would entail a thorough assessment of the genetic resources in forestry.

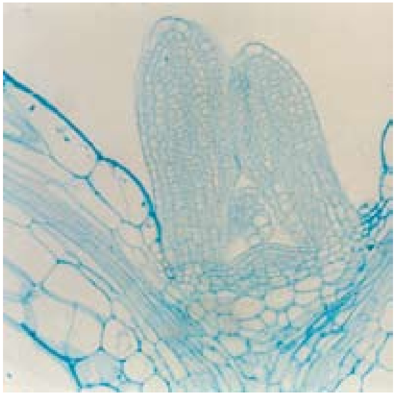
Recommended actions

Achieving sustainability is a challenge that can be addressed through the mobilisation of knowledge-based resources. The outlook needs to be holistic: we cannot afford to improve only one component of sustainability.

Plant and tree genomics are likely to provide adequate tools for improving productivity and qualities while managing natural resources and protecting the environment. Even if we anticipate a major contribution from plant improvement, it is obvious that other tools, from agronomy to farm management and from agri-chemistry to crop monitoring, will also contribute to addressing the challenge.

In addition to defining clear research goals, it is of vital importance to set up an action plan that moves from basic research to the development of crops and trees – with a major focus on the main European crops – with novel features. Finally, it is important to provide farmers with new commercial varieties and optimised farming practices based on specific monitoring tools. Two parallel strategies should be followed. The first one uses biotechnological and transgenesis approaches. The second one combines the new techniques of '-omics' with traditional breeding approaches, including QTL analysis and marker-assisted breeding. There are, of course, possible cross-links between these two approaches. For every candidate gene, it is possible to seek superior alleles within the existing plant material, as well as to pursue a strategy of genetic engineering to transfer performing alleles from distantly related species. In addition, new tools have been developed, such as tilling, which potentially combine the power of functional genomics with non-transgenic approaches. Genomics, with its many facets, has become one of the fastest-evolving areas of science. This means new tools will inevitably emerge in the coming years. The translation of this research agenda into running projects should be sufficiently flexible to integrate promising new tools and approaches.





Challenge four: Vibrant and competitive basic research

[Ref.: C4]

Vibrant basic research is essential for EU competitiveness in plant-based industries. In the knowledge-based economy of the future, competitive and innovative new products will spring from fundamental discoveries. Knowledge and intellectual property will be critical to fulfilling our goals of securing healthy, nutritious and safe food; developing valuable 'green' products; providing cheap, reliable and durable sources of bio-energy and biofuels; making agriculture and landscape management more sustainable and economical; as well as building up the human resources and infrastructure that are needed to enhance the competitiveness of basic European plant research in a rapidly changing world.

Back to basics

If we were to compare the development of knowledge to the structure of a house, then basic research is the foundations of the house. Without pursuing the fundamental enquiry that is basic research, we would not develop a sufficient understanding to innovate. The discovery of the double-helix structure of DNA is a case in point, without which many of the life sciences and biotechnologies we have come to depend on today would not have been possible.

EU plant scientists perform outstanding research on numerous aspects of plant life and are making prominent contributions to the 2010 goal of first-pass understanding of the function of all 29 000 Arabidopsis genes – the first complete 'parts list' of a plant. The cutting edge of basic plant research is rapidly evolving from understanding the functions of single genes to studying networks of genes that control complex biological processes. This new era of systems biology enables us to determine how the interconnected networks of genes and gene products work together in steering biological processes, for instance, to produce fruit and grain, or to determine the performance of the plant under different specific environmental conditions. Systems biology will reveal how natural genetic variation creates biodiversity and, together with innovative genomic technologies, will cause a paradigm shift in how we breed plants in the future.

It will replace trial and error with targeted and predictive breeding to deliver desired new traits and varieties. EU plant scientists are playing a key role in these important advances. Vibrant basic research will deliver the knowledge and tools to generate new crops and novel industrial processes. Agriculture and the sustainable production of renewable resources will remain one of the most important pillars of the European knowledge-based economy and a critical source of employment and income for large segments of European society.

Basic plant science research in Europe is and always has been world class. However, recent years have seen the EU lose ground against its major rivals. While a renewed commitment to invest more in fundamental research will pay dividends in terms of innovative new products, it is also likely to revolutionise plant breeding by greatly reducing its dependence on the traditional 'trial and error' approach. Consequently, there is now a major opportunity and a compelling case for a strong and sustained investment in basic research to enhance Europe's competitiveness.

Knowledge-based building blocks
Skilled human resources are an essential building block for competitiveness. Supporting the mobility, in particular of young scientists, will help to widen their skill base and to develop links within and between the academic and industrial research environments. Additional key infrastructures need to be made available to guarantee access to biological and genetic resources, including access to well-developed bioinformatics and data mining capabilities.

To be able to translate exciting academic findings into benefits for European society requires closer co-operation between academia and industry. This will help to channel some academic research more towards solving real-world problems and will also involve industry in the latest scientific developments. Better European plant research co-operation and coordination is an overarching goal of this Technology Platform. This needs to be complemented by stronger co-operation at the international level, which should address scientific challenges of a global scale, such as sustainable agriculture, and support developing countries in their efforts to strengthen their knowledge and capabilities so as to meet their own needs.

The specific goals with deliverables that will be explored under this challenge are:

1. **Genome sequences of European crops and major pathogens**
2. **Detailing the parts list of genomes**
3. **From gene to phenotype**
4. **Systems biology and prediction of novel traits**
5. **Building human resources, infrastructure and networking**
   - Human resource training and skill management
   - Building research infrastructures
   - European networks – co-operation and coordination

Goal one: Genome sequences of European crops and major pathogens

[Ref.: C4.G1]

Genome sequences have become the primary resource of basic knowledge of our crop plants and model species, such as Arabidopsis. Genome sequences provide complete inventories of genes for future research, and a knowledge base for the investigation of the additional layers of genome complexity, such as non-coding RNAs and epigenetic control. Genome sequences open up new perspectives for research to understand the differences between genotypes – both within a species and between phylogenetically related and even very distant species.

This new research paradigm must be fuelled by sustained investment in whole genome sequencing of plant species of scientific and industrial relevance to Europe: model species (e.g. the grass *Brachypodium*); lower plants with a pivotal evolutionary position; and important European crop species, such as wheat, potato, tomato, barley, sugar beet, grapevine, Brassica, as well as relevant energy crops (willow, Miscanthus and jatropha). The larger genomes, such as wheat, will require investment in the development of physical maps and bacterial artificial chromosome (BAC) libraries

In addition to the sequencing of crop genomes, the genomes of all major plant pathogens that affect important European crops need to be determined. Genome sequencing of all major European pests will greatly benefit the understanding of plant defence mechanisms and will help reduce the use of agri-chemicals and will aid in the development of disease-tolerant plants.

The whole genome sequences will provide the foundation from which the inventories of natural variants within species or closely related species can be obtained. Indeed, once a blueprint sequence is available, new technologies should enable the cheaper sequencing of closely related genomes. This provides the raw material for understanding natural genetic variation, micro-evolution and crop biodiversity at the genetic and molecular levels. Re-sequencing of crop genomes will be a key step in the development of high-density genetic maps and will greatly facilitate marker-assisted breeding.

The extensive data sets obtained from genome sequencing and derived data, such as gene expression profiles are currently maintained in specialised databases. In the near future, the volumes and complexity of biological data needs to be managed, distributed and analysed in entirely new ways, using new statistical and mathematical tools.
New generations of databases using semantic web and related technologies will be developed for scientists to make complex queries and analyses. In order to optimise the transfer of knowledge from model species (where experimental work is more efficient) to crops, strategies for cross-species comparisons needs to be established. Bioinformatics, in conjunction with experimentation, will teach us which processes are conserved and which are different or unique across species.

The EU should make major investments in genome sequencing of multiple plant species. Specialised centres for genome sequencing will add to efficiency and cost effectiveness. Central databases and stock centres for the curation and provision of information and materials and to ensure proper maintenance will need to support the different genomics programmes. This knowledge should be publicly held capital from which new intellectual property can be generated to maximise EU industrial competitiveness.

Time frame

Five years:
- Acquisition of genome sequences from selected model species and important European crops
- Large scale re-sequencing of crop and reference genomes
- Determination of the genome sequences of major plant pathogens affecting major European crops
- Development of next generation databases for model plants, selected crops and major pathogens
- Construction of physical maps of major European crops with large genomes (e.g. wheat, barley)

Ten Years:
- Acquisition of genome sequences from selected crops with large genomes (e.g. wheat, barley)


Goal two: Detailing the parts list of genomes

[Ref.: C4.G2]

Genome sequences provide the list of parts that contribute to building and sustaining plant life. However, understanding how these genomes work will require heavy investments in researching how these genomes are translated into molecular, cellular and organismal activities. The integration of genome-wide transcriptomics (preferably with tiling arrays) with effective platforms to study the metabolome and proteome remains a major challenge that must be solved. Technologies should be developed to detect *in planta* protein-protein interactions, protein-metabolite interactions, protein activities and metabolite fluxes. In addition, much more insight needs to be gained on how non-coding RNAs are involved in the regulation of gene expression, both at the level of transcription and setting of durable epigenetic modifications. New technologies must be developed to downscale the material that is needed and ultimately to analyse molecules and biological processes at cellular and subcellular resolution. As systems biology requires massive quantitative genome-wide data, technologies – such as protein arrays – need to be developed to analyse simultaneously numerous possible parameters at multiple time points. Scientific convergence with other areas (nanotechnology, bio-imaging, computational biology, etc.) can provide specific new technologies that will deliver the quantum leaps necessary for these ambitious but attainable long-term goals of plant science. These objectives are also held in common with all other areas of biology.

As for genome sequencing, major investments and developments in bioinformatics will be required to allow effective storage, analysis, integration and mining of the functional data provided by these technologies. Challenges will be posed by the need to integrate information across different species, in order to maximise synergies in research on models and different crop plants.

Time frame

Five years:
- Acquisition of platforms for transcriptome analysis of the newly sequenced genomes of major European crops and their pathogens
- Development of efficient proteomics and metabolomics platforms
- Development of technologies to assay protein functions
- Development of software and database systems to handle multi-level genomics datasets

Ten years:
- Development and application of technologies for observing biological processes at the subcellular level in real time and applying these systematically to understanding plant growth, development and environmental interactions
- Acquisition of platforms for transcriptome analysis of European crops with large genomes

Goal three: From gene to phenotype

[Ref.: C4.G3]

Genome sequencing and the data generated by the '-omics' tools will deliver candidate genes that need to be analysed functionally, either by using natural mutants or by applying a transgene approach in which the gene is (ectopically) overexpressed or down regulated by, for example, RNA interference.

Currently, high-throughput platforms for analysis of a small number of functions are available only for the model plants Arabidopsis and rice, and even here improvements, such as using multiple tissue-specific or inducible promoters, must be made to understand plant function. Furthermore, Europe needs to establish phenotyping platforms for all major European crops. Such phenotyping should involve both highly automated platforms in controlled environmental conditions, as well as field-based platforms.
Furthermore, the plant evaluation platforms should allow analysis of the performance of plants under controlled or highly monitored conditions in order to select genotypes or alleles and/or genes which maximise agricultural output. Such platforms will make use of advanced imaging systems and non-destructive methods to analyse plant performance, such as fluorescence measurements of photosynthesis, hyperspectral imaging, NMR or X-ray imaging of root architecture or functional tomography like positron emission tomography. These technologies require major investments and expertise-support and will allow quantitative understanding of dynamic responses of plants to abiotic and biotic challenges as a basis for identifying new traits.

Application of phenotyping platforms to breeding lines and other large plant populations will allow the identification of major genetic determinants for important agricultural traits, such as grain yield, harvesting index, flowering time, nitrogen and water use efficiency, drought tolerance, pathogen resistance, etc. New tilling-based collections with mutations in all genes, in conjunction with phenotyping platforms, will help identify the alleles in genes affecting major crop traits.

New technologies must be developed to make the functional analysis of transgenes more effective by eliminating variability due to position effects. These technologies should allow site-specific integration of transgenes in predetermined chromosomal locations or even homologous recombination. Improved transgene analysis will become important as scientists grow to realise that the successful engineering of pathways will require the modification of multiple genes or their simultaneous introduction.
To this end, new gene-delivery systems in which multiple genes can be tested in parallel will need to be developed. Finally, new technologies, such as re-sequencing, promise to accelerate dramatically the process of mutation detection. This will enable much more rapid progress in genetic analysis in multiple genetic backgrounds.

Time frame

Five years:
- Establishment of phenotyping platforms for major crops
- Development of tilling collections for major European crops
- Application of re-sequencing technologies for high throughput genetic analysis.

Ten years:
- Establishment of phenotyping platforms for major crops with large genomes
- Development of tilling collections for major European crops with large genome sizes
- Availability of site-specific integration systems for all major crops
- Extensive combinations of mutations to reveal major new levels of control and integration of biological processes


Goal four: Systems biology and prediction of novel traits

[Ref.: C4.G4]

A fourth major focus of basic research in this new era should be to understand how multiple genes function in concert to affect key processes in plant development and environmental interactions, metabolism and physiology. Using concepts from control engineering to understand the systems properties – robustness, modularity, positive and negative feedback loops – of biological processes and complex traits should aid the development and exploitation of new crop properties not apparent from knowledge of the individual components. The EU, with its strength in the mathematical, physical and biological sciences and its long tradition of collaborative interdisciplinary research should, with appropriate support, lead the world in the systems biology of plants.

One illustrative application would be the modelling of plant architecture. At present, computer programmes are being used to enhance understanding of the genetic networks underlying growth patterns and the acquisition of cellular architecture and organ shape. Future research should focus on complex gene, protein and metabolite interaction circuits that produce plant architecture as 'emergent property', including in the interaction with environmental inputs. Ultimately, the understanding of plant developmental biology garnered from experiments in the area should be represented using computer algorithms that faithfully reproduce these emergent properties. Scientists and breeders should be able to explore different plant architectures *in silico* so as to grow diverse forms according to known relationships in gene, protein and metabolite networks.

Systems biology research should be established for all basic biological processes relevant to crop productivity and quality, such as metabolic pathways; signalling systems, i.e. sensors and networks. This covers the regulatory networks controlling gene expression and protein activity; the dynamic cell – cell structure and function – from the molecular to the cellular scale; cell division to differentiation; plant development and architecture; plant response to the biotic and abiotic environment. Research in these areas should be supported through the development of computational tools for modelling genetic, biochemical and the plant signalling networks that underlie these processes.

Ultimately, computer models should allow us to predict which genes need to be altered in order to obtain a desired trait in a specific environmental scenario. Such prediction can be experimentally tested using the phenotyping platforms. The applications of such prediction could be tremendous and are likely to revolutionise current plant breeding and crop improvement. Ultimately, it will be possible to improve plants by design.

Time frame

Five years:
- The definition of the regulatory logic of simple biological systems
- Development of modelling tools for plant growth and architecture

Ten years:
- The modelling of all basic biological processes in plants

Twenty years:
- The understanding of the regulatory logic of all fundamental processes in plants: why and how this logic permits trait plasticity during evolution and domestication, within and across species. Ultimately, models should allow the definition of which genes and processes needs to be modified in order to obtain a given desired trait

Goal five: Building human resources, infrastructure and networking

[Ref.: C4.G5]

Human resources, research infrastructures and networks are three crucial building blocks of this Strategic Research Agenda. This involves the training and flexibility of researchers and scientists, state-of-the-art facilities for research and technology development in general, and strong networking on both the European and global levels.

With regard to the human resource factor, three issues need to be addressed effectively in order to attract and deploy talented young scientists: training, mobility and career perspective. The existing education and training infrastructure should be complemented with additional schemes that respond to the specific needs for multidisciplinary research of integrated and systems biology. In addition, novel mechanisms for career development are needed to promote higher flexibility and movement of scientific talent around Europe, as well as between academia and industry.

Deliverable one: Human resource training and skill management

[Ref.: C4.G5.D1]

Rapidly evolving fields of science and technology are typically driven by young and talented scientists. The proper management of this talent – through training and mobility opportunities – is a critical success factor. Each generation of scientists is educated according to the fashions and norms of the time.
Recent trends, such as interdisciplinary science (including bioinformatics, computational and systems biology) and emerging research fields (such as ecogenomics) create novel educational needs. In the coming decades, education and training should cater for both new fields, such as bioinformatics, biomathematics, and more traditional ones, such as botany, ecology and breeding.

In the field of plant biotechnology and genomics, the mobility of scientists is critical: scientists need to be able to move flexibly between disciplines, between countries and between academic and private research labs. This mobility requires new funding schemes overcoming the restrictions currently in place.

Training platforms and a virtual training centre in plant science
Numerous training programmes exist throughout Europe. However, these are not always sufficient or adequately coordinated. The key is to combine coordination and flexibility. Training platforms need to be established that are very flexible in subject, capacity and timing to respond efficiently to the needs of scientists and students. To achieve this, a database of experts and host organisations should be established, supported by a flexible funding scheme to cover the direct costs. The platforms could comprise both sabbaticals and advanced courses.

One rapid way of attracting talented young scientists and counteracting the fragmentation of European science is to create a virtual training network that may, one day, evolve into an international graduate school in plant sciences. This initiative would link all major research centres in plant biotechnology and genomics in Europe. It would support short-term exchanges of young scientists through mobility and infrastructure programmes.

Scientist mobility programmes
A number of high-quality laboratories exist throughout Europe. Connecting these in the fields of genomics, bioinformatics, physiology and ecology will truly integrate these disparate disciplines. Another growing need is to allow scientists from new Member States based elsewhere in Europe to return to their country of origin, while offering them decent conditions for continuing their research.

Finally, the exchange between academia and industry needs urgent stimulation in order to make European science a world leader in this area. New programmes are needed to complement existing ones.

- Strong post-doctoral fellowship programmes to connect high-quality European laboratories already exist. Marie Curie Researcher Training Networks (RTNs) provide an essential instrument for improving collaboration between scientists from different disciplines.
- 'Landing grants' for scientists from new Member States returning to their countries. In the future, scientists returning to their country of origin or going to other countries with less-developed science infrastructure, should receive a landing grant, including financing of equipment and an infrastructure contribution. This will promote the exchange of scientists between Member States throughout the EU, while counteracting the brain drain to developed countries outside of the EU and enhance scientific capacity in developing countries. The programme will require a combination of Marie Curie and/or structural funds.
- Exchange grants between academia and industry. In Europe, the exchange of scientists between academia and industry is primarily unidirectional from academia to industry. A mechanism allowing scientists to return from industry to academia would promote better mutual understanding and closer relations between the two sectors. Possible measures include establishing exchange grants between academia and industry, the removal of restrictions in current exchange grants, or the provision of incentives for switching between academia and industry. The Marie Curie actions need to attract different age groups, ranging from PhD students and post-docs to senior scientists.

Time frame

Five years:
- Establish the virtual training centre in plant science for PhD students
- Exchange grants for a transition between academia and industry established in selected Member States
- First landing grants for scientists from new Member States

Ten years:
- Virtual training centre in plant science for PhD students and post-docs operating with national funding
- Extended landing grants for scientists from new Member States

Twenty years:
- European graduate schools in plant science
- Landing grants become a common scheme to promote science in less-advanced regions in Europe

Deliverable two: Building research infrastructures

[Ref.: C4.G5.D2]

Europe's competitiveness in plant genomics and biotechnology hinges on keeping its research infrastructure up to date. This includes centres of high-throughput genomic research, genetic resource centres for the maintenance and distribution of genetic collections, phenotyping centres and biocomputing centres that maintain biological databases and develop tools for mining the data. These need to be upgraded regularly to keep up with the march of technology.

Essential for genomics research are high-throughput or large-scale biology requiring specialised research facilities equipped with costly instruments, robots and computers. Consequently, the implementation of an ambitious research programme must address these infrastructure needs. There are three different types of infrastructures:
- Specialised centres for high-throughput genomics research: genome sequencing and functional genomics
- Centres for the maintenance and distribution of the immense collections of genetic information resources developed in the different genomics programmes
- Centres for data storage and curation, outfitted with state-of-the-art databases that allow flexible queries (mining) of data across genomics platforms and plant species

High-throughput genomics infrastructure

The technology platforms for structural and functional genomics are currently located in a number of genomics centres throughout Europe. These institutions also offer services to the scientific community and are involved in technology development.

The continued investment in the genome sequencing of plant species and associated micro-organisms will require the boosting of sequencing capacity. Likewise, the expansion of functional genomics research into a number of different plant species will have to be met with an increasing capacity for functional genomics platforms (transcriptome, proteome and metabolome). Finally the translation of basic knowledge into crop improvement will require the establishment of novel phenotyping facilities for addressing genome plasticity and genotype x environment interactions.

Genetic resource centres

The genomics revolution has considerably increased the responsibility of stock centres in the collection, maintenance, curation and distribution of diverse types of molecular and genetic resources. With ever more plant species being subjected to genome mapping research, the demands on stock centres will increase exponentially, with new large collections of molecular resources (genomic libraries, cDNA clones, etc.) and genetic resources (mutagenised lines, activation/silencing lines, introgression/substitution lines, recombinant inbreds, and near isogenic lines). In parallel, the growing concern over the loss of biodiversity will further extend these needs to well-curated collections of plant accession lines representing the full breadth of natural diversity, including races of different types of plant pathogens (bacteria, fungi, insects and worms).

While specific research projects provide the funds for generating and collecting these large resources, the funding for their curation and maintenance is often lacking, putting in jeopardy the future of these highly valuable resources. For this reason, the proper structuring of genetic resource centres should be an important objective, with emphasis on high-standard traceability and quality assurance, coordination to avoid redundancy while maintaining security, and efficient access to the scientific community, both public and private.

Phenotyping centres

Plant phenotyping requires specific technological developments and expertise. It will be crucial to develop a network of centres for high-throughput, as well as very specific, detailed analysis of plant function. These institutions should also integrate systematic control of environmental conditions that are relevant for plant performance with respect to spatial and temporal exposure (for example, differential control of root and shoot parameters). These centres should provide access for the European research community and plant industry to sophisticated phenotyping systems. Phenotyping centres will also need to have significant capacity to develop new technologies dedicated to quantifying plant performance as an important input into systems biology and breeding. In addition, laboratory systems phenotyping will also have to address field conditions to support breeding programmes.

Bioinformatics and database infrastructure

The rapid increase in the generation of biological data is placing increasing and special demands on data storage, retrieval and analysis systems. While the storage of large amounts of novel sequence data is adequately covered by the central databases, the annotation of genome sequences, together with the comparative analysis of genome sequences, is an ongoing effort. Additionally, the large amounts of functional genomics data create a need for specialised databases to provide high-quality, curated data for functional analyses. There is a growing need to compare and integrate datasets from different platforms and different plant species and from races of different types of plant pathogens (bacteria, fungi, insects and worms). The successful realisation of integrative and systems biology will require integrated database systems allowing large-scale comparative molecular analyses between various plant species. Developing reliable predictions of the outcome of genetic modifications will be crucial for the development of new varieties and transgenic plants.

European bioinformatics centres should be responsible for data storage and for actively developing new tools for genome annotation and comparative genomics so as to support the translation of knowledge between model or bridge species and crop species. In addition, they should provide the necessary database architectures for the diverse types of molecular and functional information, ranging from gene ontologies, expression data, regulatory elements, gene and protein data (enzymatic activity, cellular localisation, pathways, interactions, mutant phenotypes, 3D structure, and post-translational modification). To achieve this, the institutions must continuously increase their storage capacity to keep up with the dataflow, establish interoperability with other data centres worldwide, and create interactivity between different levels of data.

Time frame

Five years:

- Establish high-throughput and large-scale biology centres in plant genomics
- Develop novel high-throughput plant phenotyping technologies and integration into environment simulation systems
- Establish genetic resource centres for collection and distribution of diverse types of molecular and genetic resources

Ten years:

- Establish a network of European plant phenotyping centres
- Develop and integrate European bioinformatics and database centres for functional genomics data

Deliverable three: European networks – co-operation and coordination

[Ref.: C4.G5.D3]

The networking of Europe's plant biotechnology research needs to be strengthened at three different levels. At one level, the EU needs to better network the scientific community itself through the establishment of a virtual centre for plant science research. The second level involves better interaction between academia and industry with an emphasis on improved knowledge and technology transfer. Finally, the Union's efforts in the field of plant research should be coordinated with those of other parts of the world.

Coordination is crucial to the global competitiveness of the European research effort. It should help to achieve the critical mass of resources needed for the realisation of the ambitious goals of the Technology Platform by overcoming the current fragmentation and duplication of research efforts where it occurs. It should involve closer coordination between research centres and research groups in line with the paradigm shift towards integrated biology. To this end, we propose to create a virtual centre for plant science research.

In addition to the coordination of academic research at the European level, there is a need for a closer interaction between academic and industrial research. This is particularly critical for achieving an effective translation of basic knowledge into the development of novel and improved crops. Finally, Europe's plant research should be properly embedded within the international context. Obviously, it would make no sense to duplicate costly projects, such as genome sequencing, which are being carried out elsewhere in the world, and the sharing of precious genomics resources with other countries could present clear win-win opportunities.

A virtual centre for plant science research could bring together the leading European groups in plant science within a single dynamic framework. It would aim to maximise the impact and visibility of plant science research in Europe. It would help attract the best senior researchers, young brains and financing, as well as promote the coordination of research. This centre could provide a database of research centres and capabilities, ongoing research activities and job openings in the field.

Transfer of knowledge between academia and industry

Academic research institutions in Europe are much less connected to industry than, for example, in the United States. European academic institutions have a comparatively poor track record in commercialising discoveries from basic research, including protecting intellectual property (IP) and designing early process and product prototypes. Academic scientists are generally not very knowledgeable about patenting and have limited knowledge of industry needs and of potential business opportunities.

Consequently, the lack of close interactions between academia and industry means that public investment in basic research is not generating optimal return and fails to stimulate industrial technological innovation. In plant biotechnology, many of the early basic discoveries in plant genetic engineering were made in European academic labs, but their commercial spin-offs were produced by US companies. Another important barrier is the high cost of intellectual property protection in the EU compared with the rest of the world.

Different mechanisms could remedy this situation. These include special grants or programmes to stimulate early and active interaction between research institutions performing basic research and private companies developing prototypes and commercialising innovations. Special programmes are required to stimulate a better understanding by academic researchers of intellectual property protection, relevant manufacturing processes, the industrial environment and potential commercial opportunities. Finally, the European patent situation needs to be harmonised to reduce costs.

International co-operation with developed and developing countries

Many of the goals of this Technology Platform are also relevant to the rest of the world. Consequently, much of the present Strategic Research Agenda could provide opportunities for broader international co-operation with both developed and developing countries. International collaboration would be particularly suitable for high-cost genome-sequencing projects where the main deliverable is fundamental knowledge that is publicly held. Indeed, many plant genomes have been or are being sequenced by international consortia: Arabidopsis, rice, Medicago and tomato. Ambitious programmes, such as the Arabidopsis 2010 project, also involve international collaborations.

The Technology Platform could explore future opportunities for international collaboration, wherever possible both with developed countries and developing countries. Of particular interest would be large sequencing projects (such as wheat), functional genomics projects on model species and the identification of international flagship projects, such as the engineering of plants for specific bio-based products. One-to-one partnerships between institutes or university departments must be established on a larger scale to take advantage of the complementary scientific skills and financial support. In this way, one can build, over time, successful win-win partnerships. Partnerships with developing countries could be supported by such organisations as the Rockefeller Foundation, the Gates Foundation, the World Bank, and various UN agencies.

Time frame

Five years:
- Develop detailed, modular structure and a financing plan for the virtual centre, and seek financing to build modules and maintain centre
- Identification of international collaborative projects for genome sequencing of model and crop species and functional genomics projects focusing on model species
- Secure grants and develop programmes for 'transfer seminar' between academia and industry to provide education on patenting and intellectual property protection, information on industrial processes and Good Manufacturing Processes (GMP) regulations, and to build a vibrant economic environment for commercial clients in plant biotechnology

Ten years:
- Establishment of international partnerships in plant genomics and biotechnology
- Public-private joint ventures between academic institutions and private companies in selected product areas

Challenge five: Consumer choice and good governance

[Ref.: C5]

The European Union can reap massive rewards from modern plant sciences for its citizens, consumers and companies – enhancing Europe's competitiveness while simultaneously improving our quality of life. However, to get the most out of modern plant sciences requires the right blend of two major ingredients: public and consumer involvement in the research agenda and an appropriate legal framework, including for the coexistence of different plant types, their derived products and various farming practices.

Seeds of understanding
Science's main mission is to serve society. In order to fulfil this important mandate, the plant sector community needs to pay close attention to the needs of citizens, communicate its endeavours more clearly, and involve society at large in helping to set and review the research agenda.

In many emerging scientific fields – such as the life sciences, in general, and plant genomics, in particular – a certain amount of public doubt has entered the equation. This is partly caused by the difficulty that the public has in understanding the real risks and a lack or awareness of the benefits, a failure by stakeholders to communicate effectively with the broader community about these, and insufficient public involvement in the research and decision-making processes.

In recent years, the EU has invested heavily in bringing science closer to the citizen and in ensuring that the plant sector community is a part of, rather than apart from, society. The Union has launched numerous initiatives to make science more popular and to promote better governance. In addition to regaining public trust, such efforts are designed to make research policy more efficient, accountable and democratic.

Multicultural Europe
Embracing 27 Member States, nearly 500 million citizens, and more than 20 official languages, the EU is a big and diverse place. This diversity is reflected in the broad range of cultures and views, not just between countries but also within them. In addition, Europe is a geographically varied place and is home to many forms – one could say cultures – of agriculture.

All this diversity is enriching but it is also a challenge. Although Europeans share many fundamental values, striking a balance between their varied needs and outlooks is a delicate exercise. For over half a century, Europe has prospered on a 'live and let live' mentality that has sought to build a system in which people have the freedom to fulfil their desires without harming or infringing on the rights of others.

A major challenge for the EU in the 21st century will be to forge a legal, regulatory and financial framework that will enable scientific progress to improve our collective quality of life and our economic competitiveness, while allowing us to make the choices that most suit our ideals.

Challenge five focuses on three goals to meet the issues covered in this challenge. These goal with deliverables are:

1. Public and consumer involvement

- Knowledge of plants

- Improve mutual trust between the public and the plant sector community
- Plants are fun

2. Ethics and food security

- Multidisciplinary academic forum
- Enabling a wider discussion between experts and society

3. Legal and financial environment

- Competitive options for crop management
- Technologies reducing gene flow
- Improved public funding
- Creative public-private partnerships
- Novel private investment

Goal one: Public and consumer involvement

[Ref.: C5.G1]

Plants are not only essential in our modern civilisation; they are also the roots of almost all societies. Ownership, social hierarchies, and economics structures stem from the human need to cultivate plants that provided for basic needs. But in today's urbanised, interconnected, processed and packaged societies, we are less aware of this foundation and of our dependence on plants. Only when agriculture fails or is flawed does that dependence become apparent.

Plant scientists and the plant breeding and plant biotechnology public and private sectors have been unsuccessful in their attempts to discuss genetically modified plants with the general public. The problem is not that the public does not understand genetic modification. The problem, to a large extent, is that the public does not recognise the importance of agriculture, does not know about the evolution of our field crop plants, or about plant breeding and its role in enabling agriculture to support a growing population sustainably[1]. Furthermore, plants are distant and non-anthropomorphic, and are perceived as dull and boring. People do not know what has been achieved with plants and they do not know what is possible. In a sense, genetic modification is the only interesting thing to happen to plants in a century. Unfortunately, "interesting" translates as "different", and people are always suspicious of difference.

In recent years, the plant scientific and industrial sectors have taken a defensive and largely reactive position in the GM debate, and have failed to gain the trust of the general public and politicians. The challenge for the 21st century is to regain the trust of citizens in the application of plant research and biotechnology. This goal will not be attained if the focus of the discussion is solely on genetic modification. What is needed is a much broader approach which aims to rekindle interest in plants per se among a range of stakeholders. The approach is neither pro-GM nor anti-GM, since this debate may prove to be a temporary sideshow, but it needs to be decidedly pro-plant and pro-consumer and pro-consumer and pro-combining the advantages of all technologies and methods.

The approach must engage public stakeholder groups (e.g. farmers, consumers, unions, etc). in plant science research planning and policy decisions. Plant scientists must get involved because if the importance of plants to European society is not communicated, it will be much more difficult to engender public support. Emerging democratic models of science communication and models for public participation in R&D planning and policy will be key to developing technologies that are demanded and accepted by society.

There is also the need to communicate better with the public regarding risk assessments of different plant biotechnological applications. The debate is currently focused on the risks associated with GM technology and there is little discussion of its benefits, or the risks associated with other agricultural techniques and the risks – economic, environmental, and cultural – that are inherent in the status quo.

The general thrust of the proposal on communication is to mobilise the plant sector community and to engage both opinion leaders and the general public. Communication is a two-way process of information transfer, but we recognise that the relevant information has to go beyond the transfer of facts (important though that is) from those that have the information (the plant sector community) to those who do not (the public and opinion formers). Communication is not a process of passive osmosis, whereby the assembly of a sufficient body of data and the passage of time will result in a general equalisation of information levels. Communication is an active process requiring directed efforts, some of which are required to assemble the relevant information, but most of which are needed to transform the information into an appropriate form, and to open the necessary channels to allow the transfer to occur.

Having said that the communication process needs to be active, it should also be said that we do not regard the public or their elected representatives as 'empty vessels' into which we must insert 'understanding' or 'consent'. Furthermore, among the mechanisms that we envisage using are processes that 'democratise' plant science not only by making it more accessible and by restoring the forgotten cultural context, but also by giving the public a direct say in the direction that it takes.

Europe should invest in building an environment in which understanding and respect between the public and the plant sector community are facilitated and promoted. This would encompass a European network of professionals that is multidisciplinary (involving plant scientists but also economists, sociologists and journalists) and capable of generating suitable resources. Another, equally vital component would be the need to address the cultural and structural constraints to better communication and increased interest. This implies that we need to address the insularity and isolationism of the plant sector

[1] A recent Eurobarometer survey of what Europeans think about environmental issues revealed that GM plants only ranked number ten on the list of perceived risks to the environment (water and air pollution, manmade disasters and climate change coming top of the list). Surprisingly, 40% of respondents felt insufficiently informed about the benefits and risks surrounding GM.

professional, and reengage the interest of the public.

There are, we believe, three key contributors that need to be put in place. These are explored in more detail below. In no particular order, they are:

- Increasing popular knowledge of plants
- Improving mutual trust between the public and the plant sector community
- Making plants fun

Deliverable one: Knowledge of plants [Ref.: C5.G1.D1]

The key to increasing knowledge of plants is to increase interest in plants. The information strategy that needs to be developed must place plants in the context of everyday life. Basic plant science research is largely paid for from the public purse, and plant sector stakeholders need to recognise the need to convince the public of their work. We do not want to encourage plant experts to see this as a professional obligation: we want them to have fun doing it so that the fun and interest inherent in being a plant scientist is also transmitted along with the information (see Re-humanising plant science below).

Increased awareness among plant sector community of public 'holistic' thinking [Ref.: C5.G1.D1.S1]

The plant sector community is often accused of being detached from the reality of public thinking. However, the public is also remote from scientific thinking; there is a huge gulf between what the public knows or believes to be true and what researchers believe to be true (based on their latest research and the accumulated body of scientific information). However, it would be unreasonable to expect the public to bridge that gulf by assimilating the latest in scientific knowledge. It would be unreasonable, too, to expect the public to switch any time soon to a scientific mode of thinking. Thus, the onus falls on the sectors' community to do most of the bridging that is necessary in this regard.

A number of mechanisms could enhance the plant sector community's ability to communicate with the general public. This goes far beyond what is frequently regarded as the appropriate response to questions of communication, the preparation of simplified descriptive documentation of plant science issues, solutions, and the implications of the latest finding.

The starting point should be to set an objective of increasing researchers' understanding of the way the public thinks about scientific endeavour in general and plant-related endeavours specifically. This would not take the form of surveys of public opinion but would involve training stakeholders to act as antennae of local public opinion and to take whatever opportunities to present and discuss their own views in public fora.

The necessary activities should follow two strands: voluntary interactions with the public, and compulsory activities including the institution of 'public interaction' as a required component of a PhD.

Better understanding of safety-based regulation [Ref.: C5.G1.D1.S2]

The EU and international regulatory environment as it relates to the development and use of both traditional and innovative plants and plant products is highly complex. Information about this and how it functions does not generally reach the majority of EU (and in fact world) citizens. The importance of providing clear and easily understandable information to citizens on legally binding rules concerning product safety, together with balanced risk communication, cannot be understated. This communication activity is one that should be undertaken by all involved: the research community, product developers, growers, manufacturers, retailers and the regulatory authorities.

Deliverable two: Improve mutual trust between the public and the plant sector community [Ref.: C5.G1.D2]

A very important plank of the communication strand is the definition of the starting point for debate. Most discussions in the field are not dialogues in that they usually take place between 'people who know' (or think they know) and 'people who don't know'. Therefore, debate often takes the form of a lecture, or trading the validity of different positions. Plant scientists insist that plant science must be paramount. But this can quickly bring them into conflict with people who believe equally fervently that the economic good must be paramount, or that environmental considerations must rule the day, or that public opinion must be the guiding influence on the course of events.

The approach that we should adopt is to accept that all discussions start from a position of shared or mutual ignorance. It should not be too difficult for researchers to accept a position of not knowing: the reality is that the complete genomic sequences that now exist for a number of plant species highlight what we do not know in a more precise way. They add little to the store of knowledge and even less to the store of useful knowledge. The scientific position has always been that as the circle of light increases, so too does the circumference of darkness, to paraphrase the famous French scientist Louis Pasteur.

The advantages of starting discussion from a position of shared ignorance are that initial defensiveness is avoided, knowledge-based decisions are implicitly welcomed but without the antagonism of presupposing whose knowledge that should be, new knowledge is welcomed (which provides a mandate for plant science).

Science is the engine that powers modern societies, and like the engines of modern cars, most science remains mysterious and inaccessible, a hidden force under the vehicle's bonnet that requires advanced technical knowledge to understand and adjust. It is only acceptable for the engine to remain hidden and ineffable as long as the machine is both reliable and perceived as being reliable.
Recent events in the plant sector, particularly in the area of genetic modification of plants, have aroused some adverse public attention, and it is no longer a certainty that all members of the general public trust either the nature or the direction of plant science. For its part, the plant sector community no longer trusts the general public to behave or think rationally about the plant sector: the engine no longer trusts the driver. A primary focus of this SRA is to re-establish mutual trust between the plant sector community, the general public, and the decision-makers who influence both.

The democratisation of plant science [Ref.: C5.G1.D2.S1]

The distribution of funding for plant research is determined either within the walls of private companies or behind closed doors within the boards of research funding bodies or institutes. Not only seem the specifics of any given proposal to be kept secret, but the nature of the process also seems mysterious. The consequences of this are manifold. The public may not realise how much scrutiny research proposals are subjected to. People do not know how expensive scientific research is, nor are they aware of the cumulative nature of scientific inquiry.

The public may not perceive that behind every proposal is a committed individual or group whose livelihood depends on a successful grant process. It may not see that the science-funding process is competitive and continuous. Research programmes are often dehumanised and the public may lose sight of the human face of plant science: the joy of discovery and the pain of public misunderstanding. It may not realise the difficulty of switching from one research priority to another. It may not see the cultural side of science.

One of the most effective mechanisms for engaging the interest of anyone in anything is to give them a stake in the decision-making process. At present, this engagement occurs only at the political level. By expressing concerns about plant biotechnology and genetics, for instance, the general public has succeeded in convincing many of its elected representatives that funds for certain kinds of research should be cut. In turn, research funders, such as the European Commission and many of the national research authorities, have backed away from previous research commitments in plant science.

Where the public has been positively and actively engaged in taking decisions about science and biotechnology, the outcome has been rather more positive. At the beginning of the 1990s, Denmark allowed a citizens' jury to influence its parliament's decision on the release of recombinant organisms into the environment. The result was that the issues were taken seriously and aired extensively. A Swiss referendum on GMOs similarly attracted much attention and, ultimately, an outcome that allowed the development and use of recombinant organisms to proceed. A 'jury' exercise in the UK that was orchestrated by the Science Museum to mimic the Danish example, however, failed to engage the attention of the British public. This was partly because the UK has no history of formal public involvement in technical or political decisions, but it largely boiled down to the fact that the jury was to have no direct influence on any decisions that were to be made.

In most of the EU, the public has only two mechanisms for registering its opinions on plant science: directly through its spending behaviour and very indirectly through the political process. In both cases, the retailers and the politicians have no reason to support an unpopular position (even though it might be a superficial one) and every reason to fear the consequences of opposing a popular position. On the question of GM foods, it is perhaps unsurprising that many retailers and politicians ran for cover.

The SRA should formulate new mechanisms and models through which public stakeholders can be involved more directly in some of the decision that are made at both local and national levels. At the local level, for instance, a plant research institute could establish a system whereby local stakeholders, with adequate representation and accountability, vote on the way that a certain percentage of its research budget was spent. Candidate projects would have been pre-selected through scientific peer review and the public would vote – either through a local meeting or a mechanism involving local media – on which would receive the available support. This would ensure that the core programmes of an institute are preserved (and even protected from criticism) and yet the institute would be showing itself to be responsive to public wishes in a very direct way.

The selection of the winning project would attract valuable public attention. Through interviews in the local media and direct communication with the public, the individual cases for and against each project can be discussed at a level that is appropriate for public consumption. In addition, a number of general subjects could also be discussed: plant science, science funding, the scientific method and science communication. Moreover, the local public would, in effect, have given a mandate for plant science research in the selected area.

In collaboration with a major plant science institute, Plants for the Future could prepare a pilot project which would formulate a set of guidance materials for other institutes to use to design their own 'public vote'.

A braver, but perhaps more unlikely, option would be to allow a small proportion of the overall plant science budget of a nation (or of the EU) to be exposed to direct public scrutiny. In this case, the role of the media in bringing the decision process to the public would be crucial. The Technology Platform should formulate an outline plan for such an event and will approach both the plant science funding bodies and media outlets.

We do not believe that the future of plant science funding should be placed in its entirety in the hands of public votes. However, we recognise that the current mechanisms of science funding are isolated and self-regulating processes. It is this insularity, and the concomitant apparent lack of accountability that is, at least partly, at the root of the trust issue.

Deliverable three: Plants are fun [Ref.: C5.G1.D3]

There are a number of reasons why a key aim of this SRA is to make plants more fun. 'Fun' is shorthand for excitement and for a non-utilitarian view of our resources. Humanity is dependent on plants for nutrition, medicine, raw materials, and through their ability to fix energy from the sun and recycle carbon for maintaining the balance in the environment. Due to the political and economic importance of plants, debates on the subject tend to be highly seriously.

However, humans in many parts of the world have progressed well beyond farming at subsistence levels. Spending on food and the direct products of the agricultural system are now a small fraction of most Europeans' incomes and the proportion of the European population involved directly with agricultural production is now less than 5%. At the same time, leisure and consumerism

now employ a great deal more people and account for a much greater proportion of most people's incomes than do basic food requirements. The importance of nice-to-have products outweighs the essentials in the lives of many Europeans. A recent (non-scientific) survey in the UK suggested that teenagers were more likely to know the price of an iPod than they were to know the price of a carton of milk.

Addressing the fun aspects of plants would bring European plant science much more in line with current cultural expectations and acceptance, especially among the younger generation.
There are numerous ways, other than through formal seminars and workshops, in which information can be provided, and these may prove better at improving understanding of plant science, breeding and agricultural production. For instance, at the University of Sheffield, where there has been considerable work done around the ethics and communication of biotechnology, educators from India have shown how it is possible to use traditional Indian dance as a way to convey the scientific, legal and ethical issues that are raised by modern agriculture. Theatre and music can play an important role in broadening the knowledge base around biotechnology and agriculture.

There is already good work being undertaken to achieve a greater involvement of the public. For instance, at http://www.foundation-imagine.org a Dutch project for school children has been established that aims to make science (including biotechnology) more fun and interesting and, consequently, more relevant to their lives. Another website in the UK, http://www/ytouring.org.uk provides information on a touring theatre that performs plays dealing with problems associated with modern science.

Thus, in the first instance, we should explore links to the world of art and recreation. These could include (but are not restricted to) rap music (lyrical content), fashion (new material), video art horticulture, decoration and the mysterious and surprising side of nature. In addition, new media could open 'virtual labs' to bring the life of the professional plant scientist to the attention of the general public in a more interactive way. This would complement local schemes that involve physical or intellectual exchanges between the worlds of education and science (often funded by the same or related ministries). Thus, networking between science teachers could be encouraged, schools could call on science residents, pupils might be encouraged to shadow scientists at work, or researchers could compile 'scientist@work' diaries.

The general public often associates forest landscapes with 'wilderness'. Thus, a discussion around how managed forests actually are, would prove useful, interesting and 'fun' when communicating about plant science and human impact on the environment.

'Re-humanisation' of plant scientists [Ref.: C5.G1.D3.S1]

The plant research community and its industrial offshoots is a community of diverse individuals who share some common goals but are otherwise multidimensional in terms of age, sex, political persuasion, philosophy, hobbies, habits, and so on. However, the individuals within that community are largely anonymous and relatively unknown outside their very specific fields – although a few in each European country are called on by the media to comment on developments.

The result of this anonymity is that the public does not distinguish between individual plant scientists. Plant science is conflated with research-based companies or with "greedy multinationals" in an amorphous mass with no real human face, and with no distinguishing shades of opinion.

The re-humanisation of plant scientists is a critical part of re-engagement with the public. We are not suggesting that every plant scientist needs to become a media star. We are suggesting that part of the professional remit in plant science is to establish contact with local organisations which have a reason to be interested in plants.

The SRA proposes three mechanisms for facilitating this contact. The first is an efficient mechanism, such as a 'clearing house', for plant scientists to participate in various public engagements, such as school visits, seminars to non-biology students, as well as gatherings of teachers, gardeners, cooks, herbalists, flower arrangers, golfers, hikers, environmentalists, and other people with a specific or indirect interest in plants. The clearing house would (a) compile details of potential speakers; (b) make it known that there were people available to talk on certain plant-related topics; (c) provide a list of organisations which might be interested in talks on plants; and (d) develop a contact system that put the two together.

The second mechanism is a resource list that speakers could draw on. This would include graphics and photographs that might be used in talks to the public; a set of example arguments that could be used to make a particular point; and outlines for talks on a particular subject. In the first instance, these resources could be compiled at various national nodes but the Technology Platform would also play a role in professionalising and internationalising nationally collected resources. The Technology Platform would also help to stimulate the generation of resources by companies or institutes, and liaise with publishers to ensure that appropriate copyright clearance had been obtained.

The third mechanism would be the provision of public-speaking guidelines and advice. We do not intend to expend large amounts of resources on training, media skills, and the like. Instead, we should encourage institutional initiatives in which direct interaction with the public is a key component, and trust that the institutions will recognise that communications skills training is an integral part of what they need to do.

A fourth element of communication is the recognition of the need to segment the public – see it as a diverse collection of individuals and groups – and understand who one is trying to address in any particular initiative. It is abundantly clear that the general public is not a unified whole, either in its general composition or, more particularly, in its attitudes to plant science, its knowledge of plants, or the access points from which it might be possible to generate an interest in plant science. The role of the Technology Platform should be to map out these various "publics" and establish some general guidelines for plant science professionals.

An important task of the Technology Platform should be to educate information providers (in essence, the plant science community) as to the subtleties of communication – so that they can learn to present their information in a way that is useful and engaging. The presentation of information will differ for each of the groups one might want to reach. Books and newspapers may be an effective way of reaching educated laypeople in general, but e-mails, chatrooms, the worldwide web and text messaging might be more effective vehicles for communicating with the young and gadget-conscious. For many people, direct engagement – conversation, lectures, shared activities – may be a more effective form of communication than anything based on remote information provision. For others, the broadcast media or science festivals might be appropriate channels.

Plants for the Future should institute pilot schemes at a national level that could be readily adapted to circumstances elsewhere. Each of a number of countries would undertake its own national study in a given area, building on existing efforts. It would be charged with disseminating its findings and its methodology to other countries.

Time frame

The following research activities should be undertaken to tackle the issues covered by the three deliverables with scopes in goal one of challenge five.

Five years:

- Training stakeholders to act as antennae of local public opinion and to take whatever opportunities to present and discuss their own views in public fora.
- Establish communication mechanisms, readily accessible to EU citizens, that simply and clearly show that human, animal and environmental safety of innovative plant products is ensured through the EU regulatory system which requires pre-market safety assessment and approval
- Develop and continue to update databases of willing public lecturers, theatre and other groups with an interest in communicating on plant science; public groups that may be interested in plant science (including schools); copyright-free background material appropriate for public talks and teaching; broadcast organisations (with up-to-date contacts) who might commission programmes on plants
- Engage with professional plant science organisations in order to institute a "public" stream into their meetings and organisations
- Design and implement training kits to help young researchers (PhD and post-docs) interact with the public
- Examine the feasibility of making this a compulsory part of PhD training in plant science
- Run pilot schemes in three Member States as models for the 'democratisation of plant science'
- Assess the feasibility of extending the model to other Member States
- Assess routes in each Member State to providing plant science input into primary and secondary education syllabuses
- Establish a working group on public education with a primary brief to identify the crossover between plant science and the primary and secondary education syllabuses
- Develop and adapt for national use materials appropriate for use in primary and secondary education
- Develop scripts and treatments for broadcast programme ideas
- Develop European plant science portal which will enable access to copyright-free background material, databases of public groups, willing lecturers, educational materials

Ten years:

- Implement compulsory PhD requirement for 'Interactions with the public'
- Establish formal mechanisms for updating plant science input to school syllabuses
- Extend 'democratisation of plant science' as widely as possible

Twenty years:

- Continue to update databases, syllabuses, background materials
- Encourage continued 'democratisation of plant science'

Goal two: Ethics and food security

[Ref.: C5.G2]

Both the Plants for the Future vision paper and this Strategic Research Agenda point to a future in which European agriculture will become more diversified. This rapid rate of progress implies a lot change on the horizon. In order to deal with this, a number of issues need to be addressed so that producers in the food and non-food sectors, consumers and our environment can fully benefit from this diversification.

These include putting in place farming and production systems that are safe for consumers and the environment. Consumers should have the freedom to choose which products they wish to consume which implies that the coexistence of different speciality crops and farming systems needs to be guaranteed in an economically feasible manner.

The European classification of farming systems and agricultural products – conventional, GM and organic – on which current regulation is largely based, may not reflect the full variety of possible future diversifications. New research may be needed to ensure that the coexistence and the safety of production systems can be established. This may include crop management tools to minimise the co-mingling of different product types, specific techniques to control pollen flow or pollen viability, tools to detect naturally occurring cross pollination and enhance the traceability of products obtained from different cropping systems, etc.

Freedom of consumer choice is also an important aspect of the ethical debate that needs to balance the potentially conflicting demands of providing consumers with the 'natural' and quality food they desire, while boosting agricultural production – with the help of new technologies – to feed a growing human population and provide it with more renewable bio-based materials and energy.

Investing in plants for the future

The realisation of the objectives of this Strategic Research Agenda will require strong financial commitments from both the public and the private sectors, and more specifically an increase in the level of research funding to bring it up to international standards. In the last decade, the funding of plant biotechnology in Europe – both public and private – has stalled or even dropped. This has largely been the effect of the public controversy surrounding the risks and benefits of GM plants and derivative foods.

There is now a considerable funding gap between the EU and many of its major rivals, such as the United States and even China and India. Since 1998, the number of research projects in the area has fallen off by 37%. In the private sector, the decrease has been over 60%.

This has been accompanied by the closing down of industrial plant biotechnology research centres or their relocation to other parts of the world. This situation is also affecting the classical breeding sectors, which – although they do not produce transgenic plants – are highly dependent on advances in modern biotechnologies. Consequently, the EU's competitiveness in plant genomics and biotechnology hinges on how effectively it can remedy this situation by taking the debate one step further. Only then a favourable investment and market environment can be restored. A much more open discussion among all stakeholders concerned about the development and applications of the plant sector to the benefit of society in Europe and globally. This will include ethical, food security and environmental issues.

Ethics

The European public at large has raised concerns about the ethics of plant genomics and biotechnology in crop development and farming. While this section deals with the legal environment, including legislation relating to safety and coexistence, it is useful to provide some comment on ethics, although these are not specific to any one technology or industry.

The study of ethics pulls together theories of moral judgement as they relate and are practiced by different cultures. Culture itself is grounded on values – religious beliefs, family traditions, ways of land use, arts, sports, literature and also science and technology. For a given culture, this builds a network of principles or baselines for decision, on which humans depend to determine acceptable behaviour. One specific area of culture cannot replace another, but each influences the others. In the case of global technologies, such as agricultural biotechnology and plant genomics, it is necessary to consider different value systems in different regions of the world.

Global justice

The idea of plant products referring to the basic value of justice is mainly a case for ethical argumentation because of actual and predicted global scarcities and shortages of supply of plant products (e.g. of food and animal feed). In this argument, the determining criterion is a matter of quantity and, thus, possible objections against the safe use of specific plant development technologies, related to their specific qualities, can be neglected here.

A crucial point for ethics is long-term sustainability, not only for developed, highly productive societies, but also for global society as a whole (consider, for instance, the concept of 'strong sustainability', as described by Ott and Döring 2004). Globally, the amount of arable land is limited, while world population is still rising and land use practices are often still far from sustainable. For instance, within the EU, it is probable that political options for 'set aside' land will in time disappear under the pressure of global food and feed and other renewable plant product needs. The recent and rapidly increasing demand for farmland for crop cultivation that will provide renewable resources for manufacturing industries and energy, such as bio-fuels, is already resulting in competition for limited land resources.

Needs and wants
Any ethical discussion should include an understanding and consideration of society's needs and wants, as these are not the same. Basic needs for food (sufficient carbohydrates, proteins, fatty acids, vitamins, etc.) carry a high moral priority because food is essential for survival and subsistence. Even so, these depend very much on the society and level of deprivation within each. The concept of need is very different to most EU consumers than that which is experienced in many developing countries. It must be recognised that need, in a physical sense, may be overridden by cultural "phobias" or traditions that deter the use of a foodstuff, even where famine exists. There are tribes living on the shores of lakes in Africa that will not eat fish, even though other food is scarce. Although justice is addressed here, the concept of distributive justice may also need explanation and clarification. These issues will come into public debate in the future.

Wants are aspirations for a better, more comfortable life. As the world gets smaller through rapidly evolving communication and information technologies, humans will not only be better informed about food shortages occurring elsewhere, but in a multinational society such as the European Union, it will become more difficult to turn away from the responsibility of solving such problems. Individual comfort might, to some extent, become less important compared with individual moral responsibility for the 'global family' (Raskin et al. 2002). Policy-makers will have to set up a legal framework to coordinate intra- and intergenerational justice, especially in the wake of global climate change – the plant sector communityhas already identified this phenomenon as a driver for accelerated research and development, if basic human and animal needs are to be met.

In recent years, there has been a rapidly growing interest in the use of renewable resources, and in particular renewable and sustainable energy products. In some parts of the world, especially the United States and South America, there has been an increase in the cultivation of sugar and starch-producing plants to produce bioethanol and other biofuels. In 2006, the EU harvested more hectares of oilseed rape to produce bio-diesel than vegetable oil.

This global move to use farmland to grow energy crops is already bringing about changes in the prices of food and feedstuffs on world commodity markets and is resulting in questions about global food security. While there is a need to use plant genomics and biotechnologies to ensure that these bio-energy crops are efficient, there is also a need to look into the ethics surrounding the use of agricultural lands for the production of non-food and feed crops.

The plant science and plant breeding communities must seriously consider that they, almost exclusively, have the scientific understanding and tools that can help to bring about sustainable global plant production.

The application of modern plant genomics and biotechnologies in the field of crop production may become better accepted when it is understood that they are used to mimic 'natural' biological survival mechanisms, thus helping to achieve global food and feed security.

Freedom and consumer choice
The individual's freedom to choose products from a specific type of 'nature' will become a stronger argument in the future, resulting from globalisation with different but interacting cultural influences. The consumer's choice of products is to be respected in order to guarantee this freedom. This includes reliable rules and codes of practice for coexistence of the different farming practices. The moral argument of 'freedom' relates to the ethical principle of the autonomy and free will of the individual. That means that plant genomics and biotechnology have to serve different people with different rationalities and sensibilities.

Deliverable one: Multidisciplinary academic forum [Ref.: C5.G2.D1]

Promote interdisciplinary discussions [Ref.: C5.G2.D1.S1]
Plant researchers should hold more interdisciplinary discussions with the cultural, religious and social sciences as they research and develop only those plants which will provide both basic needs and wants, and shape landscapes and public open spaces.

The European Union has an established European Group on Ethics in Science and New Technologies (EGE). The EGE is already working on a project considering the ethical aspects of modern agriculture. Plants for the Future and its network of stakeholders should become involved in this project[2].

Carefully consider the goals of plant science [Ref.: C5.G2.D1.S2]
As the cultivated plant is both used as a living organism and as a vehicle to provide needed and wanted plant products, plant scientists should reconsider the goals to be achieved by the different technologies used in plant development. For some objectives, such as the production of pharmaceutical proteins, plants might be the exclusive production system. In such a case, there seems to be an ethical 'bottleneck' in arguing against plant biotechnology-derived crops.

Deliverable two: Enabling a wider discussion between experts and society [Ref.: C5.G2.D2]
The symbolism of 'nature' refers to what the plant stands for in relation to our anthropocentric worldview. In order to be accepted, including in the short term, modern plant genomics and biotechnologies must stand for something good that can generally be regarded as such even in a world with different rationalities and cultures. Plant scientists, researchers and developers must openly state and communicate the goal for breeding and be open to public discussion.

Time frame

The following actions should be taken to tackle the issues covered by the two deliverables with scopes in goal two of challenge five

[2] AGE: Opinion : N° 23 on the 'Ethical aspects of modern developments in agriculture with specific attention to sustainable agriculture'

Five years:

- Establish fora where plant science researchers and developers can better interact with the academic community studying cultural, religious and social sciences
- Set up fora where the plant science, social science and public sectors can engage in open and transparent dialogue about plants and plant science

Ten years:

- Establish mechanisms to include in primary and secondary school curricula teaching materials showing the importance of plants to humankind, the history of agriculture and the plants humankind has chosen to use for agricultural and other purposes, together with the relevance of modern plant science and research

Goal three: Legal and financial environment [Ref.: C5.G3]

Legal environment
There are numerous legal instruments related to the development and use of plants. They cover animal human and environmental safety, as well as intellectual property rights associated with plant variety development and the transport across national boundaries of plants and plant materials. In fact, legislation governing the sale, use and movement of plants has been in place in some countries for more than a century.

With respect to the development of new plant varieties and innovative uses of plants, key points of regulation/legislation should be considered to meet the long-term objectives set out in the Vision Paper and Strategic Research Agenda. Current EU legislation focuses on achieving two different objectives.

1. **Safety:** For certain new plant varieties, a notification of its planned cultivation and food or feed uses is required. This is followed by a safety assessment and, if approved, it may be released on to EU markets. Safety considerations are also taken into account under the World Trade Organisation's sanitary and phytosanitary scheme and also under the International Plant Protection Convention (IPPC) that focuses primarily on preventing the movement around the world of plant pests (fungal, viral and bacterial diseases and insect pests).
2. **Consumer choice:** Examples of plant-related legislation that aim to maximise consumer choice include EU labelling rules for organic, GM and conventional food products.

Safety-based legislation
EU legislation makes direct reference to the precautionary principle. The Commission states clearly that actions based on the precautionary principle should be proportional to the chosen level of protection; related to risk management to ensure that risk is minimised; non-discriminatory in their application; and consistent with similar measures already taken. They should also be based on an examination of the potential benefits and costs; subject to review in the light of new scientific data; and capable of assigning responsibility for producing the scientific evidence necessary for a more comprehensive risk assessment.

In considering the use of mandatory EU safety legislation that requires a pre-marketing assessment and approval of new plants, the SRA proposes the following recommendations:

- Legislation must be 'enabling' if society is to reap the benefits of innovation in the public and private plant science, research and development communities.
- The chosen protection standards should be clearly defined and common across product types.
- Baselines for comparison of new plant types and uses for safety assessment purposes should be consistent with the baselines used to evaluate their traditional counterparts.
- The existing and extensive scientific database on plants and their impact/interaction on human and animal health and the environment should form the foundation baseline for safety assessments.
- Safety assessment of new plant types should not only focus on potential risk, but should also be open to a consideration of potential benefits.
- Any mandatory notification, assessment and approval procedure should be clear, transparent and consistently implemented across the EU.
- Where there are requirements for monitoring of potential unanticipated effects or changes in the environment for an approved new plant product, these should be considered in a holistic manner that includes a consideration of changes resulting from plants developed using traditional technologies, and that both should be considered against the same baseline information.
- Where there are national rules, these must be interpreted and applied consistently with respect to European legislation.
- Any mandatory approval procedure should be manageable by public plant variety developers, as well as private SMEs and larger plant breeding companies.
- It should be recognised that there is a significant number of public research laboratories in the EU and in developing countries that may not be able to afford the necessary systems. This should be taken into account with respect to the 'proportionality' statements made above.

Regulatory approval procedures can impose a considerable resource burden on innovators. If this is unnecessarily excessive, publicly funded innovators and small and medium-sized enterprises (SMEs) might be excluded from taking innovative plant types to the marketplace. Complex regulation often involves numerous regulatory agencies in different policy areas, such as agriculture, health, environment and trade. These include the European Food Safety Authority (EFSA), Member State governments and public authorities, as well as the European Commission and other EU institutions.

To achieve the agreed upon levels of safety protection, while ensuring that regulation is enabling, the SRA recommends that there is central and effective coordination of any mandatory approval process – the EFSA has already been established as a 'one-door, one-key' entry point for GMO risk assessment – and that decision-making is transparent.

A question of choice
Participants in the Technology Platform consultation process and workshops recognised that consumer choice is not limited just to the type of product but also the method of production chosen by the farmers and food manufacturers. European citi-

zens are already offered a wide variety of plant products derived using different production methods. Perhaps the most obvious examples are foods produced using modern agricultural practices and those produced according to organic principles. Although producing organic food is a voluntary scheme, in order to qualify for the EU's 'organic' label, strict production rules must be adhered to.

There are now mandatory, legally binding rules that aim to provide consumers with information to permit them to make an informed choice with respect to some production technologies. The EU GM food and Feed Regulation and GM Traceability and Labelling Regulation require notification and assessment prior to marketing of all GMOs and products derived from GMOs, as well as appropriate labelling indicating their GM origin.

To promote informed choices, it is important that any voluntary labelling system must be truthful and not misleading. In addition, where mandatory labelling systems are deemed necessary to enable informed choice, they should be constructed in such a way as to be truthful and not prone to misinterpretation as safety warnings. They should not result in discrimination against innovative plant products as this would limit choice.

A related issue in the provision of choice is managing the coexistence of different farming methods[3]. The European Commission recommends that the choice of one production type and the setting up of associated standards should not prohibit the choice of another product type.

One final point relates to the risk that may result from <u>not</u> moving forward with an innovative technology. There is a tendency, especially taking into account the way that the precautionary principle is applied to new innovative products, to ignore the evaluation of continuing with traditional conventional products and or practices compared with the innovative new product or process. It is important to consider a comparison of the old with the new in this respect. A standardised benefit assessment mechanism would be an important component of any risk management communication programme.

Coexistence measures enabling choice

The coexistence of different production systems is not a new issue in agriculture. In conventional farming, segregated agricultural production lines and channels have been practiced for years. These include specialty 'Euroflint' maize grown for human consumption and waxy maize grown for the starch industry. Both of these production chains successfully coexist in European agriculture with the production of yellow dent field maize for animal feed. Another example is the production of high Erucic acid rapeseed (HEAR), a crop grown specifically for the extraction of machine lubricating oil which is quite unsuitable for use in salad and cooking oils. This HEAR production successfully coexists with the production of standard vegetable oil quality rapeseed that is used in food preparation. Other examples are malting barley for beer and barley for animal feed, and wheat for animal feed and wheat for bread production.

Over the centuries, the cultivation of each 'specialty crop' has raised the issue of coexistence with 'standard crops', namely the question of how to handle the possibility of the adventitious (unintended) presence (AP) of traces of the standard crop in the specialty crop, and vice versa. Farmers and concerned industries, through the development of good farming practices and appropriate harvesting, storage and transportation systems have adequately answered the question as to how producer choice can be ensured without jeopardising the market prospects of specialty or standard crops. This extensive experience shows that production guidelines and AP thresholds, established on a case-by-case basis, with an adequate balance between the lowest level of AP and the lowest level of additional costs, facilitate coexistence. Waxy maize commonly uses a threshold of 4% adventitious presence of feed maize.

EU coexistence guidelines

The European Commission's 2003 information note describes ten principles involved in achieving coexistence so as to provide farmers and consumers with a practical choice between conventional, organic or GM food and feed production and products. The six most significant are:

1. No form of agriculture, be it conventional, organic, or GM should be excluded in the European Union.
2. The ability to maintain different agricultural production systems is a prerequisite for providing a high degree of consumer choice.
3. Coexistence refers to the ability of farmers to make a practical choice between conventional, organic and GM crop production, in compliance with the legal obligations for labelling and/or purity standards.
4. Specific measures that might be imposed to protect the environment and/or human health, if needed, are included in the final consent of the authorisation procedure in accordance with Directive 2001/18/EC, with a legal obligation for their implementation.
5. The issue of coexistence addresses the potential economic loss and impact of the admixture of GM and non-GM crops, and the most appropriate management measures that can be taken to minimise admixture.
6. Farm structures and farming systems, and the economic and natural conditions under which farmers in the European Union operate, are extremely diverse, and efficient and cost-effective measures for coexistence vary greatly between the different parts of the European Union.

These principles form a useful basis for considering how to promote choice among producers and consumers in light of the R&D spawned by this Strategic Research Agenda.

[3] Commission Recommendation 2003/556/EC on Guidelines for the Development of National Strategies and Best Practices to Ensure the Coexistence of Genetically Modified Crops with Conventional and Organic Farming.
http://europa.eu.int/eur-lex/lex/LexUriServ/LexUriServ.do?uri=CELEX:32003H0556:EN:HTML

The cultivation of future speciality crops in the EU, be it for new food or non-food products, such as crops optimised for the efficient production of energy, is likely to have implications for the organisation of agricultural production. The challenge will be to minimise these implications.

To provide European consumers with a real choice between different foods, there should be a functioning traceability and labelling system, as well as an agricultural sector that can provide the different types of goods. The ability of the food industry to deliver a high degree of consumer choice depends on the ability of the agricultural and food processing sectors to maintain the segregation of product from the different production systems in a sustainable and economic fashion.

Maintaining free choice for farmers requires crop-specific farming practices to address the cultivation and handling of future speciality crops in agriculture and to achieve the desired level of purity, while allowing viable economies of scale in the production system. Such practices include the isolation distance of one crop from another, intervals of different numbers of years between growing the same crop in the same field, the control of volunteer plants, the use of buffer zones between crops, and guidance for handling. Since the farming systems and natural conditions under which farmers in the European Union operate are extremely diverse, coexistence measures should be crop, farm and site-specific. In France, a specific programme (POECB) evaluating coexistence between GM and non-GM maize was launched in 2002. Its results show that coexistence is possible with workable guidelines.

Risk management considerations

The establishment of safer and more environmentally friendly production methods ensures that consumer protection is a key driver for developing new food and feed production chains relying in particular on biotechnology tools. Developing techniques to restrict significantly or prevent gene flow between GM and non-GM crops in which specific safety concerns have been identified (e.g., crops modified to produce specialty non-food chemicals) would significantly improve the food and environmental safety associated with growing these crops.

There are strategies available in the design of GM plants that can be considered as 'best practice' when it comes to minimising identified and unidentified risks associated with GM plants. Thus, future generations of transgenic plants suitable for the EU market should ideally have certain characteristics. They should yield high-quality products which can be produced in a more environmentally friendly, cost-effective and sustainable manner.

Inserted transgene sequences should be minimised to ensure function. Plant host mutation is minimised by targeted insertion of gene sequences at pre-selected genome locations known to give no side effects or unknown interactions. Expression of transgenic traits should be limited to the tissues and to the conditions where they are needed – the transgene should be expressed according to biological and agronomical musts.

The desired expression of transgenic traits has to be ensured even under environmental stress and, hence, independent of plant-specific regulatory factors and superfluous expression of the transgene and the impact of unwanted stress factors. The dispersal of transgenes in the environment should be minimised. The production, testing and selling of new transgenic plants should take into account consumer demands, offering as much transparency as possible.

Considering the principles of precision biotechnology early in the development of a GM plant can help to deal better with risk and uncertainty in evaluating safety. The principles of precision biotechnology as an integral part of modern plant breeding should become standard for crop improvement and the acceptance of improved crops.

Deliverable one: Competitive options for crop management

[Ref.: C5.G3.D1]

Coexistence measures should focus on the feasibility and costs of management practices that aim to minimise adventitious gene presence, while maintaining competitiveness.

Improved control measures and refined farming practices

Scientists need to study further pollen dispersals in space – between fields, farms and regions – and identify the effects of control measures, such as isolation distance, border row management, control of volunteers and hybrids, modelling and monitoring.

Time frame

Five years:
- Collate available information and develop a comprehensive database on pollen flow and specifically the likelihood and frequency of resulting pollination events for the different crop species in different European agri-ecological zones

Ten years:
- Collate available information and develop a comprehensive database on crop seed survival in soil for different crop species in different European agri-ecological zones.

Deliverable two: Technologies reducing gene flow

[Ref.: C5.G3.D2]

Technologies can help to limit natural, but unwanted, gene transfer from GM to non-GM crops. Technologies reducing pollen flow and/or pollen viability, therefore reducing gene flow, are already available. Genomics can bring new and more efficient tools to achieve that goal.
These technologies should be of particular interest to specialist growers, such as those growing plants for pharmaceutical products and other special non-food or feed purposes.

Develop and improve existing technologies [Ref.: C5.G3.D2.S1]

Biological containment strategies, which attack the problem of gene flow at source, have been or are under development and should be further improved. There are several approaches to achieving male sterility in plants that are controlled by the nuclear or the mitochondrial genome:
- Cytoplasmic male sterility: Current methods of blocking viable pollen production take advantage of naturally occurring cytoplasmic male sterility

(cms), a maternally inherited inability to produce functional pollen. Natural sources of cms are available for many crops.

- Genic male sterility: The introduction of genetically engineered male sterility was an early strategy for gene containment that has some advantages for species where no natural cms systems have been found. The recent development of inducible promoters could provide a means of controlling fertility by conditionally expressing 'restorer genes', when required, in a male-sterile background.
- Cleistogamy: This is a process whereby self-pollination and fertilisation occurs within an unopened flower. It is another means of achieving pollen, and consequently gene, containment. Cleistogamous traits have been induced by mutation in oil seed rape.

Time frame

Five years:
- Evaluate and conduct further research into known biological systems (as described) for their potential to provide consistent and reliable gene flow prevention (containment) mechanisms

Ten years:
- Research and develop these gene 'containment' mechanisms in crop species chosen to provide specialty non-food chemicals/proteins (such as plant-made pharmaceuticals)

Identify and develop new technologies [Ref.: C5.G3.D2.S2]

A number of new technologies are currently under investigation. These include the exploitation of apoptosis, split gene technology, plastid transformation, apomixis, sexual dimorphism, and transgene mitigation.

A non-genetic approach can be used and, instead of working on the plants, one can design chemical molecules, known as gametocide, which can block, at different stages, pollen development. A few molecules of this type have already been identified; none have, so far, achieved commercial success. However, some may become commercially viable in case where a strict prevention of gene flow is needed.

Time frame

Ten years:
- Explore the potential for new biological systems that would provide the possibility to have consistent and reliable gene flow prevention (containment) mechanisms

Twenty years:
- Research and develop these new gene 'containment' mechanisms for use in crop species chosen to provide specialty non-food chemicals/proteins (e.g. plant-made pharmaceuticals)

Financial Environment

The financial environment for investments in plant genomics and biotechnology needs to be markedly improved if Europe wants to remain competitive in this field. One of the main goals of the present Strategic Research Agenda is to promote a strong consensus on the tremendous societal and economic potential of plant genomics and plant biotechnology research for Europe.

To achieve the SRA's ambitious goals will require substantial financial commitments from both the public and the private sectors. Like any investment, the commitment of substantial resources to plant biotechnology must meet return on investment criteria.

However, in this field, return on investment calculations are less straightforward than in many other areas of innovation, simply because much of the future return will be indirect. For instance, a more competitive agricultural sector will increase the profitability of conventional farming and, thus, lead to a reduction in agricultural subsidies. In addition, many of the stated goals in the SRA should benefit society as a whole, but may have no directly measurable financial returns, except that they may reduce future costs to society. Consequently, it can be argued that a large fraction of the investment in research must come from public funding and, where possible, from public-private partnerships.

Deliverable three: Improved public funding [Ref.: C5.G3.D3]

The main areas of research where public funding must be substantially increased are basic research and applied research that is or will not be covered by private funding, such as research into orphan crops and environmental research. Increased public funding at the EU, national and regional levels is required to prevent Europe from further falling behind its competitors. Furthermore, the research programmes of the Member States, the regions and the EU need to be harmonised and coordinated, such that current fragmentation and inevitable overlaps are eliminated. The recently created ERA-NET for plant genomics represents an important step in this direction.

Time frame

Five years:
- Increase public and private research financing at all levels
- Increase coordination between national programmes by bringing together relevant bodies and developing long-term strategies
- Research topics to be defined by strategic consideration (2/3 of the topics to be defined in this way)

Ten years:
- Programmes jointly coordinated and financed by public bodies at EU, national and regional level
- Research topics to be defined by strategic consideration (80% of the topics to be defined in this way)

Deliverable four: Creative public-private partnerships [Ref.: C5.G3.D4]

Although the ultimate products expected to emerge from the Strategic Research Agenda are likely to be brought to the market by industry, the high risk and the long timelines from concept through to commercialisation are such that it will be difficult or impossible to convince the private sector to make substantial investments in early-stage research. Nonetheless, the participation of industry in research is essential to ensure that the research remains targeted on deliverable product. Consequently, creative solutions are needed to generate incentives for industry participation.

For instance, joint financing with dynamic ratios of public funding and private investment are recommended for specific areas of research that have the potential of generating new added-value products and that require substantial upfront investments in basic research. In such a scheme, the public sector would finance the initial high-risk phase, while private investment would increase in the latter stages.

Time frame

Five years:
- Identify public-private research partnerships for large-scale initiatives and prepare financing plans
- Launch the first large-scale public-private partnerships

Ten years:
- Large-scale public-private research partnerships established for all major research objectives of the SRA

Twenty years:
- Continuous pipeline for large scale public-private partnerships

Deliverable five: Novel private investment

[Ref.: C5.G3.D5]

Technology development should continue to be the main driver of innovation in plant biotechnology. New leads for technology innovation are likely to result primarily from discoveries made in academic research, but the main technology providers to industry will probably be SMEs. The new technologies should be transferred from academia to innovative start-ups, which, with the support of private investment, can bring these new technologies to maturity.

What is needed are novel incentives to stimulate private investment in SMEs to develop new technologies. To mitigate the high risks, an EU plant biotech investment fund with strong public participation could be set up. New instruments currently being studied or under development by the European Investment Bank and the Commission, such as the ‘risk sharing facility’ or the ‘technology transfer accelerator fund’, could be used for this purpose.

Time frame

Five years:
- Study new instruments being developed by EC to facilitate private investment and apply to SRA as appropriate

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UPDATING THE STRATEGIC RESEARCH AGENDA

The Strategic Research Agenda (SRA) is a living document. As the social, political, economic and environmental framework is changing over time and the implementation according to the SRA is advancing, the members of the European Technology Platform “Plants for the Future” will work to update the SRA.

We foresee to publish an updated version of the complete SRA latest five years after the first version, which would be in 2012.

Until then we encourage members of the Steering Council of the Plant ETP to provide us with expert opinions on the SRA. When appropriate they should comment on the SRA and / or provide papers which will refer and be linked to specific topics in the SRA. All interested experts / parties beyond the Steering Council are encouraged to contact a member of the Steering Council to jointly work on such comments.

Such expert opinions / papers should be short and have a strict format consisting of 1) The reason for the update, 2) The reference(s) to the SRA, 3) The position itself, and 4) The author(s) names and affiliation and the date of the opinion. Papers should be submitted to the Plant ETP Executive Committee. Opinions / papers will be forwarded to the ETP’s Steering Council for adoption, and subject to a positive response the opinion / paper will be published on the Plant ETP website.

The members of the Steering Council are published at www.plantsforthefuture.eu and can be contacted via the Plant ETP secretariat at PlantTP@epsomail.org.

Selected Glossary

Abiotic stress:	Nonliving environmental factors (such as drought, extreme cold or heat, high winds) that can have harmful effects on plants.
Agri-food sector:	the sector of the economy that produces agricultural and food products.
Agribusiness:	agriculture-related industries.
Agri-food industry:	agriculture and food related industries.
Bio-economy:	all industries and economic sectors that produce, manage and otherwise exploit biological resources (and related services, supply or consumer industries), such as agriculture, food, fisheries, forestry, etc.
Biofuels:	fuels derived from living organisms, as opposed to fossil fuels.
Biomaterials:	materials derived from living organisms, as opposed to synthetic materials
Biotechnology:	technologies for cultivating, modifying or deriving products from living organisms.
Biotic stress:	Living environmental factors (such as viruses, bacteria, fungi, insects etc.) that can have harmful effects on plants.
Coexistence:	the cultivating of conventional, organic and genetically modified crops in the same area without them affecting one another.
Genetics:	science and technology of hereditary factors.
Genetic modification:	scientific technique for altering the genetic make-up of living organisms which results in genetically modified organisms (GMOs).
Forestry:	the cultivation of trees and the management of forests and woodland. Related sectors include paper and pulp industry.
Knowledge-based bio-economy (KBBE):	the knowledge-based approach to all industries and sectors of the economy which produce, utilise or manage biological resources.
Plant genomics:	the science and technology of the genetic make-up of plants.

For a more comprehensive glossary, please refer to the European Commission's website:
http://ec.europa.eu/research/biosociety/library/glossaryfind_en.cfm

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European Technology Platform
'Plants for the Future'

Strategic Research Agenda 2025

Action Plan 2007 - 2012

25th June 2007

In the following sections, the research activities necessary for each deliverable for the period from 2007 to 2012 are listed as developed in Part II of this proposal for a Strategic Research Agenda.
Activities referring to a different time frame are cited as such.

Challenge one: Healthy, safe and sufficient food and feed [Ref.: C1]

Goal one: Develop and produce sufficient, diversified and affordable high-quality plant raw materials for food products [Ref.: C1.G1]

Deliverable: Diverse and affordable raw material for food [Ref.: C1.G1.D1]

- Generation of a compendium of crop species and varieties required for maintaining food diversity.
- Creation of repositories for long-term storage of germplasm and current breeding work to maintain competitiveness of these species against non-food ones.

Deliverable: Plant raw materials with improved composition in major storage compounds [Ref.: C1.G1.D2]

- Analysis of regulatory pathways controlling the accumulation/degradation of storage compounds in different crops.
- Identification of steps needed to be modified for the improvement of global composition.

Deliverable: Plant raw materials with improved characteristics for the production of nutritionally enhanced and more attractive food [Ref.: C1.G1.D3]

- Analysis of pathways controlling the accumulation of specific metabolites/macromolecules contributing to the quality of different crops
- Identification of steps to be modified for the improvement of composition
- Identification of specific factors contributing to vegetable/fruit quality and taste
- Development of strategies for their improvement

Deliverable: Plant raw materials for food with increased and end product targeted sensory characteristics [Ref.:C1.G1.D4]

- Identification of the molecular components of plant raw materials influencing the sensory characteristics of food
- Analysis of the biochemical pathways leading to them as a basis for plant improvement. In this context, close co-operation with food specialists from industry is necessary

Deliverable: Plants with improved processing characteristics for food manufacture [Ref.:C1.G1.D5]

- In close co-operation with industry, identify the molecular components of plants that determine the post-harvest characteristics and shelf life of plant raw materials
- Analysis of the biochemical pathways leading to these compounds as a basis for plant improvement

Goal two: Produce, trace and control safe plant raw materials for feed and food [Ref.: C1.G2]

Deliverable: Reduction of toxins and other harmful components [Ref.: C1.G2.D1]

Reduction of mycotoxins [Ref.: C1.G2.D1.S1]

- Develop high-throughput techniques for toxin quantification (biochemical tools and biological assays)
- Study genetic, molecular and cellular aspects of the plant-fungal interaction in order to decipher the mechanisms regulating toxin production and synthesis
- Identify novel resistance genes for the development of transgenic wheat and barley free of mycotoxins
- Develop more comprehensive safety data on dose thresholds for adverse effects of mycotoxins to improve risk assessment

Reduction of anti-nutritional factors and undesired compounds [Ref.: C1.G2.D1.S2]

- The variety of genetic and genomic tools, including proteomic and metabolomic approaches, could be used to identify plant genes that control the synthesis of proteins or metabolites that have anti-nutritional effects.
- High throughput-screening can be used to identify germplasm lacking those genes (or alleles) which specify the synthesis of anti-nutritional factors and undesired compounds to be used later on in conventional breeding approaches.

Develop new food species by making some non food crops safer [Ref.: C1.G2.D1.S3]
No activity specified for the period 2007-2012
Reduction of heavy metals [Ref.: C1.G2.D1.S4]
No activity specified for the period 2007-2012 specified
Reduction of xenobiotics [Ref.: C1.G2.D1.S5]
No activity specified for the period 2007-2012

Deliverable: Plant raw materials which are less harmful to food [Ref.: C1.G2.D2]

- Develop innovative analytic technologies for ant-nutritive, unfavourable organisms, biological or chemicals, which are systemic to or contaminating food plants
- Analysis of processes leading to and monitoring the accumulation of deleterious compounds
- Identification and implementation of steps to be modified for the improvement of new raw material composition and for minimising quality obstacles

Deliverable: Traceability and control [Ref.: C1.G2.D3]

Ongoing activity through out the twenty years:

- When ever a new variety is developed as part of a breeding programme (as described in this SRA), in parallel it will be evaluated if a new marker has to be developed for this variety. If the conclusion is yes, this marker will be developed.

Goal three: Tailor plant raw materials for certain health benefits and specific consumer groups [Ref.: C1.G3]

Deliverable: Food for the prevention of chronic diseases – including obesity, diabetes mellitus, cardiovascular disease, stroke, hypertension [Ref.: C1.G3.D1]

Low glycemic food [Ref.: C1.G3.D1.S1]

- Identify and characterise the molecular structures of plant-derived carbohydrates which determine metabolic rate in humans
- Analyse the biochemical pathways leading to these sugars as a basis for plant improvement

Food enriched with vitamins, flavonoids, and carotenoids [Ref.: C1.G3.D1. S2]

- Transfer results in model plants to different crop plants

Polyunsaturated fatty acids (PUFA's) [Ref.: C1.G3.D1.S3]

- Identify all genes which are necessary to transfer PUFAs biosynthetic capacities from algae to higher plants

Deliverable: Reducing allergenicity/improving tolerance [Ref.: C1.G3.D2]

- Identify the plant genes for biosynthesis of gluten, especially gliadin. Analyse the underlying biochemical pathway as a basis for plant improvement

Deliverable: Food for cancer prevention [Ref.: C1.G3.D3]

Food products with anti-tumoral properties [Ref.: C1.G3.D3.S1]

- Identify plant ingredients which reduce the incidence of cancer

Goal four: High-quality, sufficient, affordable and sustainable feed [Ref.: C1.G4]

Deliverable: Quality feed for quality food [Ref.: C1.G4.D1]

Plant raw materials with optimised concentration, quality and composition of macronutrients [Ref.: C1.G4.D1.S1]

- In close collaboration with agronomists and nutritionists, assess the macronutrient characteristics needed within a plant
- Identify germplasm and genes that are important for the trait and introduce them into breeding programmes

Plant raw materials with optimised concentrations of micronutrients [Ref.: C1.G4.D1.S2]

- In close collaboration with agronomists and nutritionists, assess the micronutrient characteristics needed within a plant
- Identify germplasm and genes that are important for the trait and introduce them into breeding programmes
- Analyse the environmental effects and agricultural practices on micronutrient composition for major crops in Europe

Plant raw materials with improved palatability/ digestibility [Ref.: C1.G4.D1.S3]

- Phenotype major feed crops (grains and forages) with regard to palatability/digestibility

Challenge two: Plant-based products – chemicals and energy [Ref.: C2]

Goal one: Biochemical production [Ref.: C2.G1]

Deliverable: Pharmaceuticals [Ref.: C2.G1.D1]

A source of recombinant protein medicines [Ref.: C2.G1.D1.S1]

- The manufacture of products from genetically modified plants and entry into human clinical trials (based on good manufacturing practice)
- Science-based systems for the risk management of GM pharmaceutical production in plants
- First generation regulatory pathways for products derived from genetically modified plants
- Re-evaluation, diversification and expansion of major diseases targeted by European funding agencies, and increasing collaborative initiatives with health research agencies in developing countries
- Definition of new disease targets and commercially viable pharmaceuticals to be produced in plants
- New technologies for optimising expression and accumulation of recombinant proteins in plants
- Development of new plant-based production strategies

A source of natural products – secondary metabolites [Ref.: C2.G1.D1.S2]

- Genomic knowledge base for selected plant species.
- Coordinated programmes for the discovery of metabolic pathways and products.
- Modification of metabolic pathways to increase diversity and functionality of identified products.
- Establish collaborations with international developing country partners to work on screening programmes of indigenous flora for pharmaceutical purposes

Deliverable: Specialty chemicals and enzymes [Ref.: C2.G1.D2]

Chemicals [Ref.: C2.G1.D2.S1]

- Identification and functional characterisation of specialty chemicals, such as surfactants, flavours and fragrances from native species
- Establish best strategy for product development in close collaboration with industrial chemists and end-users
- Establish programme of rapid domestication in those cases were it is considered feasible over a relatively short time period (5-10 years)
- Build on existing knowledge to determine biosynthetic route to product in native species and clone key genes in the pathway
- Transfer key steps in product synthesis into amenable crop platform or microbial system

Industrial and technical enzymes [Ref.: C2.G1.D2.S2]

- Identification and biochemical characterisation of new plant enzymes for important industrial processes to complement or replace chemical catalysis
- Ising bioinformatics and functional genomics
- Establishment of plant 'tool boxes' for the optimal expression of recombinant microbial enzymes

Deliverable: Plant-derived oils as industrial feedstock [Ref.: C2.G1.D3]

Development of non-food crop platforms [Ref.: C2.G1.D3.S1]

- Identification and characterisation of the major bottlenecks limiting the production of high yields of unusual fatty acids, such as hydroxy, epoxy and conjugated fatty acids in both model oilseed species and oil crops
- Addressing related factors of seed biology, including capacity of engineered seeds to germinate and remain viable in subsequent generations
- Development of strategies to maximise the flux of carbon into oil during seed development in order to maximise the yield of oil per hectare (addresses demand from all application sectors)
- Evaluation of existing oilseed species diversity for functionality and initiation of rapid domestication programmes, if appropriate
- Development of non-food crop platform for industrial oil production – to include transformation and metabolic engineering

Deliverable: Polymers [Ref.: C2.G1.D4]

Starch [Ref.: C2.G1.D4.S1]

- Identification of enzymes (plant and non-plant) that can modify starch structure *in vivo*, including its molecular weight, branching pattern and introduction of substitution groups
- Enhancing understanding of the starch granule structure-function relationship.

Rubber [Ref.: C2.G1.D4.S2]

- Establishment of a generic research programme on the molecular biology and biochemistry of rubber production in guayule, Russian dandelion as well as in other rubber-producing plants, such as Goldenrod. This needs to identify the key genes involved in rubber synthesis, in the control of molecular weight and the synthesis of allergenic proteins
- Establishment of breeding and germplasm programmes for guayule and Russian dandelion
- Identification of suitable regions and agronomic practices for the cultivation of guayule and Russian dandelion, as well as the creation of field plots
- Development of efficient transformation systems for guayule and Russian dandelion

- Methods to prevent gene flow from transgenic rubber-producing plants to wild relative (in case of Russian dandelion)
- Life cycle analysis of rubber production in Europe from guayule and Russian dandelion

Polyhydroxyalkanoates [Ref.: C2.G1.D4.S3]

- Generic research programme aimed at understanding the regulation of the carbon flux of acyl-CoAs, including acetyl-CoAs
- Genetic engineering of plants for the high-level synthesis (more than 15% dry weight) of polyhydroxybutyrate homopolymer and a polyhydroxybutyrate-based copolymer containing 3-hydroxycayl-CoA of greater then 6 carbons
- Identification of model crop for the synthesis of PHA in plants, substantiated with life cycle analysis

Monomers and building blocks for biopolymer synthesis [Ref.: C2.G1.D4.S4]

- Prospective study, supported by lifecycle analysis, of the chemical building blocks most suited for production in plants versus bacteria/fungi, as well as the identification of non-food plant platforms for such production
- Identification of key enzymatic pathways in microbes, plants and animals which can be used for the synthesis of important building blocks
- Exploratory production of building blocks in model plant systems

Protein-based bioplastics or biopolymers [Ref.: C2.G1.D4.S5]

- Identification of functionalities that can be added to existing commercially abundant storage proteins to improve their properties as biopolymers
- Identification of mechanisms in plants that are used for production of block polymeric proteins in plants
- Establishment of biochemical pathways for the non-ribosomally produced polypeptides in plants

Deliverable: Fibres [Ref.: C2.G1.D5]

Improvement of plant fibres [Ref.: C2.G1.D5.S1]

Research activities are listed jointly for all scopes of this deliverable below.

Towards novel plant fibres [Ref.: C2.G1.D5.S2]

Research activities for both scopes of deliverable five, goal one, challenge two

- Increased knowledge of cell wall development in relation to fibre properties
- Development of novel plant fibres for textile applications
- Composite materials incorporating a variety of plant fibres

Goal two: Bio-energy production [Ref.: C2.G2]

Deliverable: Production of biomass [Ref.: C2.G2.D1]

Increased biomass yield and improved efficiency of water and nutrition use [Ref.: C2.G2.D1.S1]

- Genetic diversity established for selected energy crops
- Sequencing of selected energy crops completed
- Transformation technology developed for each of the key energy crops
- Plant physiology and yield screens developed

Improved composition of lignocellulosic feedstocks for biofuel production [Ref.: C2.G2.D1.S2]

No activity specified

Deliverable: Conversion of biomass [Ref.: C2.G2.D2]

No activity specified

Deliverable: Innovative concepts for whole plant utilisation [Ref.: C2.G2.D3]

No activity specified

Goal three: Enabling research for plant based products [Ref.: C2.G3]

Deliverable: Development of production platform crops and extraction processes [Ref.: C2.G3.D1]

- Choice of candidate plants to serve as starting point for conversion into green factories
- Detailed genomic, proteomic and metabolomic understanding of candidate plant species – a molecular toolbox for each plant production candidate
- Development and validation of biotechnological tools for new production crops
- Improved plant gene expression technologies
- Improved mRNA production and translational performance of mRNAs
- Developing efficient molecular evolution technology
- Developing gene replacement technology
- Improved promoter technologies
- Determining the optimal site of accumulation for groups of non-plant target compounds
- Developing technologies to optimise the targeting of compounds to specific sub-cellular locations
- Developing technologies to optimise the targeting of compounds to specific plant tissues
- Developing scale-down technologies for efficient testing of extraction procedures
- Controlled boosting of plant cell division rates

Deliverable: Systems for plant production [Ref.: C2.G3.D2]

- Development of new manufacturing strategies (for production, extraction and processing)
- Development of small-scale manufacturing infrastructure and capacity (such as containment greenhouses and bio-reactors to facilitate the entry of plant pharmaceuticals into initial human clinical trials)

Challenge three: Sustainable agriculture, forestry and landscape [Ref.: C3]

Goal one: Improve plant productivity and quality [Ref.: C3.G1]

Deliverable: Identify key drivers of plant yield productivity and stability [Ref.: C3.G1.D1]

Combining improved photosynthesis and carbon dioxide fixation with nutrient and water use efficiency to obtain elite cultivars [Ref.: C3.G1.D1.S1]

- Molecular analysis of C metabolism and of N-C nutritional relationships in different crops and trees, the signalling processes involved and the improvement of key coupling factors
- Evaluation of the consequences of carbon dioxide accumulation in the atmosphere on photosynthesis

Improving plant and tree architecture and developmental characteristics for better yields [Ref.: C3.G1.D1.S2]

- Analysis of the impact of plant architecture and developmental features on yields in different crops and trees

Analysis and improvement of factors contributing to growth and yield stability [Ref.: C3.G1.D1.S3]

- Analysis of the impact of environmental factors on growth and yield stability in different crops and trees
- Analysis of factors contributing to hybrid vigour

Deliverable: Improve the quality of plant and tree products [Ref.: C3.G1.D2]

Improve the composition of harvested products in major storage compounds [Ref.: C3.G1.D2.S1]

- Analysis of pathways controlling the accumulation of storage compounds and fibre polymers in different crops and trees
- Identification of the steps to be modified for the improvement of global composition

Improve the quality of harvested products as starting points for the production of healthy food and feed [Ref.: C3.G1.D2.S2]

- Analysis of pathways controlling the accumulation of specific metabolites/macromolecules in different crops and contributing to their quality
- Identification of the steps to be modified for the improvement of composition
- Analysis of specific factors contributing to fruit quality and taste and the development of strategies for their improvement

Reduce the negative impact of factors deleterious to quality [Ref.: C3.G1.D2.S3]

- Analysis of processes leading to the accumulation of deleterious factors
- Identification of steps to be modified for the improvement of composition

Reducing the mycotoxin contamination of crops of significant economic value [Ref.: C3.G1.D2.S4]

- Identification of the source of Fusarium resistance/ tolerance in the plant varieties of major crops, especially cereals
- Improving quality through molecular breeding, tilling and/or transgenic approaches in different crops

Deliverable: Climatic changes and plant tolerance to non-biotic factors [Ref.: C3.G1.D3]

Improve tolerance to water limitation and drought [Ref.: C3.G1.D3.S1]

- Analysis of drought tolerance processes
- Improvement of tolerance to water shortages through molecular breeding and/or transgenic approaches in different crops and ornamental plants
- Establishment of a protocol to study the adaptation to water deprivation for different plant phenophases

Improve tolerance to cold temperatures and frost [Ref.: C3.G1.D3.S2]

- Analysis of cold adaptation and tolerance processes

Improve salt tolerance [Ref.: C3.G1.D3.S3]

- Analysis of salt tolerance processes

Adapt forests to climate change: characterise and improve the tolerance of tree species to abiotic conditions [Ref.: C3.G1.D3.S4]

- Trials with different provenance to investigate the genetic control of tolerance against various abiotic conditions
- Understanding the molecular basis of tolerance and adaptability to various abiotic conditions

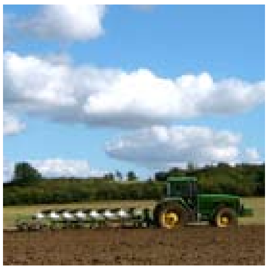
Goal two: Reduce and optimise the environmental impact of agriculture [Ref.: C3.G2]

Deliverable: Develop methods of crop protection with lower environmental impact [Ref.: C3.G2.D1]

Perform a systematic and well-balanced assessment of the environmental effects of agri-chemicals [Ref.: C3.G2.D1.S1]

- Setting up of monitoring tools for the half life of phytochemicals and their breakdown products in plant and in the environment

Real-time monitoring of epidemic events [Ref.: C3.G2.D1.S2]



- Setting up disease-monitoring tools (biochip-based, etc.)

Development of environmentally friendly alternative practices for crop protection [Ref.: C3.G2.D1.S3]

- Development of crop-targeted methods of delivery of protective agents
- Evaluation of the impact of different agricultural practices on pest and pathogen control

Identifying new, environmentally friendly weeding tools and practices [Ref.: C3.G2.D1.S4]

- Evaluation of the impact of different agricultural practices on weed control.
- Identification of putative targets for new herbicides

Deliverable: Improve tolerance and resistance to pathogens and other biotic factors [Ref.: C3.G2.D2]

Identification and analysis of genes contributing to pathogen and pest resistances in crops, forest tree species and in related wild plant species [Ref.: C3.G2.D2.S1]

- Inventory of genes contributing to host and non-host disease resistance in subject and other plant species

Management of genes contributing to pathogen and pest resistance in the field [Ref.: C3.G2.D2.S2]

- Determination of crop management techniques which avoid resistance/tolerance from a single gene

Deliverable: Improve the interaction of beneficial biotic factors [Ref.: C3.G2.D3]

Inventory of beneficialsymbiotic micro-organisms in the rhizosphere [Ref.: C3.G2.D3.S1]

- Develop molecular tools for the analysis of soil microbial functional diversity

Inventory and exploitation of molecules released by plants and trees and which play a role in their fitness in the environment [Ref.: C3.G2.D3.S2]

- Inventory of bioactive metabolites and their role

Development of biological control strategies [Ref.: C3.G2.D3.S3]

- Inventory of organisms of interest to biological control issues, and analysis of their mechanisms of action

Deliverable: Optimise the utilisation of water resources and fertilisers [Ref.: C3.G2.D4]

Develop monitoring tools and adapted agricultural practices to reduce and optimise the need for fertiliser and water [Ref.: C3.G2.D4.S1]

- New real-time monitoring tools
- Modelling of uptake, storage and utilisation of water and fertilisers by crops

Identification of the limiting steps in nutrient use efficiency and breeding crops for improved nutrient efficiency [Ref.: C3.G2.D4.S2]

- Molecular analysis of the basis of nutrient utilisation efficiency in different crops

Transfering the N-fixing ability of legumes to other crops and trees [Ref.: C3.G2.D4.S3]

- Molecular analysis of the basis of symbiotic processes in N-fixing plants

Modelling of crop and forestry systems [Ref.: C3.G2.D4.S4]

- Develop new mechanistic soil/plant digital models of the use/loss of resources

Deliverable: Reduce and optimise the environmental impact of feed [Ref.: C3.G2.D5]

Decreasing inputs in feed crop production [Ref.: C3.G2.D5.S1]

Research activities are listed jointly for all scopes of this deliverable below.

Increasing the use of legume crops [Ref.: C3.G2.D5.S2]

Research activities are listed jointly for all scopes of this deliverable below.

Increasing the sustainability of herbivore farming systems [Ref.: C3.G2.D5.S3]

Research activities are listed jointly for all scopes of this deliverable below.

Research activities for all three scopes of deliverable five, goal two, challenge three

- Use comparative genomics (of the genome sequencing of rice and model legumes) to facilitate the genetics of polyploid and allogamous species and breeding of diverse forages

Goal three: Enhance biodiversity [Ref.: C3.G3]

Deliverable: Characterise and maintain biodiversity [Ref.: C3.G3.D1]

Setting up protocols for biodiversity assessment in representative farming and forestry practices [Ref.: C3.G3.D1.S1]

- Setting up of monitoring tools

Model field ecosystems and their relations to surrounding areas [Ref.: C3.G3.D1.S2]

- Exploitation of data existing in the literature to build first generation models

Provide farmers with protocols of good agricultural practices [Ref.: C3.G3.D1.S3]

- Selection of a set of agricultural practices expected to have a positive impact on biodiversity

Deliverable: Characterise pathogen and pest biodiversity and how this affects crops [Ref.: C3.G3.D2]

Collect and exploit existing collections of plant and tree pathogens and pests, and assess their virulence

and pathogenicity on crops [Ref.: C3.G3.D2.S1]

- Selection of relevant species (viruses, bacteria, fungi, insects, nematodes, etc.) and inventory of their pathogenicity on representative crop accessions and related wild species in different physiological conditions

Identify virulence and pathogenicity genes [Ref.: C3.G3.D2.S2]

- Selection of genomes to be sequenced and their 'shotgun' sequencing

Analyse genetic diversity of pathogens at the molecular level [Ref.: C3.G3.D2.S3]

- Analysis of factors affecting the biodiversity of pathogens

Deliverable: Characterise the biodiversity of plant and tree genetic resources [Ref.: C3.G3.D3]

Core collections established for major crops and trees [Ref.: C3.G3.D3.S1]

- Genotyping of all accessions

Phenotype analysis of all relevant traits, including biochemical traits [Ref.: C3.G3.D3.S2]

- Metabolome and storage compounds

Evolutionary genomics and linkage disequilibrium analysis of biodiversity components [Ref.: C3.G3.D3.S3]

- Coverage of the genome with an optimal number of SNP markers
- Genotyping of the core collection

Creating segregating populations from core collections and mapping agronomic traits through QTL analysis [Ref.: C3.G3.D3.S4]

- Selection of accessions of interest and generation of recombinant materia.
- QTL analysis of traits of interest: including physiological and biochemical traits

Deliverable: Improve crop and tree biodiversity through the introgression of traits from wild relatives [Ref.: C3.G3.D4]

Creating advanced back cross populations and sets of substitution lines [Ref.: C3.G3.D4.S1]

- Inventory of wild relatives of a crop and analysis of cross fertility

Introgression of specific loci in elite varieties [Ref.: C3.G3.D4.S2]

No activity specified for the period 2007-2012

Deliverable: Domesticate new crops and trees [Ref.: C3.G3.D5]

Evaluating the potential of new crops and trees [Ref.: C3.G3.D5.S1]

- Survey of traits of interest

Exploit synteny to identify and modify domestication genes [Ref.: C3.G3.D5.S2]

No activity specified for the period 2007-2012

Perform conventional breeding for yield and agronomic performance [Ref.: C3.G3.D5.S3]

No activity specified for the period 2007-2012

Challenge four: Vibrant and competitive basic research [Ref.: C4]

Goal one: Genome sequences of European crops and major pathogens [Ref.: C4.G1]

- Acquisition of genome sequences from selected model species and important European crops
- Large scale re-sequencing of crop and reference genomes
- Determination of the genome sequences of major plant pathogens affecting major European crops
- Development of next generation databases for model plants, selected crops and major pathogens
- Construction of physical maps of major European crops with large genomes (e.g. wheat, barley)

Goal two: Detailing the parts list of genomes [Ref.: C4.G2]

- Acquisition of platforms for transcriptome analysis of the newly sequenced genomes of major European crops and their pathogens
- Development of efficient proteomics and metabolomics platforms
- Development of technologies to assay protein functions
- Development of software and database systems to handle multi-level genomics datasets

Goal three: From gene to phenotype [Ref.: C4.G3]

- Establishment of phenotyping platforms for major crops
- Development of tilling collections for major European crops
- Application of re-sequencing technologies for high throughput genetic analysis.

Goal four: Systems biology and prediction of novel traits [Ref.: C4.G4]

- The definition of the regulatory logic of simple biological systems
- Development of modelling tools for plant growth and architecture

Goal five: Building human resources, infrastructure and networking [Ref.: C4.G5]

Deliverable: Human resource training and skill management [Ref.: C4.G5.D1]
- Establish the virtual training centre in plant science for PhD students
- Exchange grants for a transition between academia and industry established in selected Member States
- First landing grants for scientists from new Member States

Deliverable: Building research infrastructures [Ref.: C4.G5.D2]
- Establish high-throughput and large-scale biology centres in plant genomics
- Develop novel high-throughput plant phenotyping technologies and integration into environment simulation systems
- Establish genetic resource centres for collection and distribution of diverse types of molecular and genetic resources

Deliverable: European networks – co-operation and coordination [Ref.: C4.G5.D3]
- Develop detailed, modular structure and a financing plan for the virtual centre, and seek financing to build modules and maintain centre
- Identification of international collaborative projects for genome sequencing of model and crop species and functional genomics projects focusing on model species
- Secure grants and develop programmes for ‘transfer seminar’ between academia and industry to provide education on patenting and intellectual property protection, information on industrial processes and Good Manufacturing Processes (GMP) regulations, and to build a vibrant economic environment for commercial clients in plant biotechnology

Challenge five: Consumer choice and good governance [Ref.: C5]

Goal one: Public and consumer involvement [Ref.: C5.G1]

Deliverable: Knowledge of plants [Ref.: C5.G1.D1]

Increased awareness among plant sector community of public 'holistic' thinking [Ref.: C5.G1.D1.S1]
Research activities are listed jointly for all deliverables and scopes of this goal below.

Better understanding of safety-based regulation [Ref.: C5.G1.D1.S2]
Research activities are listed jointly for all deliverables and scopes of this goal below.

Deliverable: Improve mutual trust between the public and the plant sector community [Ref.: C5.G1.D2]

The democratisation of plant science [Ref.: C5.G1.D2.S1]
Research activities are listed jointly for all deliverables and scopes of this goal below.

Deliverable: Plants are fun [Ref.: C5.G1.D3]

'Re-humanisation' of plant scientists [Ref.: C5.G1.D3.S1]

Research activities for all three deliverables with scopes of goal one in challenge five

- Training stakeholders to act as antennae of local public opinion and to take whatever opportunities to present and discuss their own views in public fora.
- Establish communication mechanisms, readily accessible to EU citizens, that simply and clearly show that human, animal and environmental safety of innovative plant products is ensured through the EU regulatory system which requires pre-market safety assessment and approval
- Develop and continue to update databases of willing public lecturers, theatre and other groups with an interest in communicating on plant science; public groups that may be interested in plant science (including schools); copyright-free background material appropriate for public talks and teaching; broadcast organisations (with up-to-date contacts) who might commission programmes on plants
- Engage with professional plant science organisations in order to institute a "public" stream into their meetings and organisations
- Design and implement training kits to help young researchers (PhD and post-docs) interact with the public
- Examine the feasibility of making this a compulsory part of PhD training in plant science
- Run pilot schemes in three Member States as models for the 'democratisation of plant science'
- Assess the feasibility of extending the model to other Member States
- Assess routes in each Member State to providing plant science input into primary and secondary education syllabuses
- Establish a working group on public education with a primary brief to identify the crossover between plant science and the primary and secondary education syllabuses
- Develop and adapt for national use materials appropriate for use in primary and secondary education
- Develop scripts and treatments for broadcast programme ideas
- Develop European plant science portal which will enable access to copyright-free background material, databases of public groups, willing lecturers, educational materials

Goal two: Ethics and food security [Ref.: C5.G2]

Deliverable: Multidisciplinary academic forum [Ref.: C5.G2.D1]

Promote interdisciplinary discussions [Ref.: C5.G2.D1.S1]
Research activities are listed jointly for all deliverables and scopes of this goal below.

Carefully consider the goals of plant science [Ref.: C5.G2.D1.S2]
Research activities are listed jointly for all deliverables and scopes of this goal below.

Deliverable: Enabling a wider discussion between experts and society [Ref.: C5.G2.D2]

Research activities for both deliverables with scopes of goal two in challenge five

- Establish fora where plant science researchers and developers can better interact with the academic community studying cultural, religious and social sciences
- Set up fora where the plant science, social science and public sectors can engage in open and transparent dialogue about plants and plant science

Goal three: Legal and financial environment [Ref.: C5.G3]

Legal Environment

Deliverable: Competitive options for crop management [Ref.: C5.G3.D1]

- Collate available information and develop a comprehensive database on pollen flow and specifically the likelihood and frequency of resulting pollination events for the different crop species in different European agri-ecological zones

Deliverable: Technologies reducing gene flow [Ref.: C5.G3.D2]

Develop and improve existing technologies [Ref.: C5.G3.D2.S1]

- Evaluate and conduct further research into known biological systems (as described) for their potential to provide consistent and reliable gene flow prevention (containment) mechanisms

Identify and develop new technologies [Ref.: C5.G3.D2.S2]

No activity specified for the period 2007-2012

Financial Environment

Deliverable: Improved public funding [Ref.: C5.G3.D3]

- Increase public and private research financing at all levels
- Increase coordination between national programmes by bringing together relevant bodies and developing long-term strategies
- Research topics to be defined by strategic consideration (2/3 of the topics to be defined in this way)

Deliverable: Creative public-private partnerships [Ref.: C5.G3.D4]

- Identify public-private research partnerships for large-scale initiatives and prepare financing plans
- Launch the first large-scale public-private partnerships

Deliverable: Novel private investment [Ref.: C5.G3.D5]

- Study new instruments being developed by EC to facilitate private investment and apply to SRA as appropriate

NOTES:

NOTES:

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