2020 EUROPEAN VISION FOR PLANT SCIENCE

Rationale of meeting

It is clear that human society currently faces numerous challenges, such as an increasing demand for food, competition for land use and climate change. Ameliorating these problems will be dependent, in part, on increasing our knowledge of plant biology and ecology. To ensure plant science moves forward in a productive manner in the next decade the EU 2020 vision for plant science workshop was held in Bonn on the 2-3 June 2008, to identify the current major challenges in biology and investigate how plants, particularly Arabidopsis, could provide solutions to these challenges.

The workshop was organised by the Biotechnology and Biological Sciences Research Council (UK) and Deutsche Forschungsgemeinschaft (Germany).

Conclusions

- Strategic investment is needed in plant science to meet the needs of secure food production and sustainable agriculture practises.
- Arabidopsis has underpinned the genomic revolution and knowledge of gene structure and function in plants that is enabling the genomic and targeted approaches being used in plant breeding today.
- Predictive biology will become a central theme of plant science in the next decade. Arabidopsis will play an essential role in the parameterisation of plant biology providing data, techniques and technologies necessary to generate predictive models of plant responses to the environment.
- To enable the translation of knowledge from plant models to crops, coordinated and funded strategies are needed to put in place public genome datasets, to maintain genetic diversity collections and extend mapping populations in crop species that will enable identification of genes underpinning key traits.
- Arabidopsis research is an essential component of a continuum of plant biology from fundamental to translational plant science.

Contents

Report Outline

In preparing this report our aim has been to summarise the views of the workshop participants as to the major goals of Plant Science over the coming decade. Achievement of many of these goals will depend on the use of model systems and at the same time provide exciting opportunities for crop improvement.

Report Authors

Jim Beynon – University of Warwick, UK
George Coupland – MPI Koeln, Germany
Ian Graham – CNAP, University of York, UK
Klaus Harter - ZMBP, Universität Tübingen, Germany

Plant Science research is essential for the development of strategies for sustainable crop production

Why invest in Plant Science?

Plant science, largely through the adoption and development of model systems, continues to deliver breakthroughs in our knowledge and understanding about plants in particular and basic biological processes in general. The need for translation of this knowledge into application is greater than ever given the demand for step-changes in agricultural productivity that we now face in the 21st Century. We need to produce more food for humans and feed for animals to meet the dietary needs of an increasing human population. At the same time we also need to produce biomass and specialty products from plants that can be used as sustainable industrial feedstocks and biofuels to replace fossil derived products. All this has to be achieved in a sustainable manner in light of societal and global pressures to lower inputs such as fertilizers, irrigation, and agrochemicals and improve the carbon balance of crop production. We also need to take into consideration that all this has to occur against the backdrop of global warming, changes in weather patterns, increasing atmospheric CO_2, continuing water shortages, loss of arable land and erosion of valuable topsoil.

Plant scientists are well placed to meet the challenges

Two decades of investment in the plant model Arabidopsis have generated a fully annotated genome, a wealth of tools and resources, which in turn have led to the creation of a flourishing international community of researchers. This investment has created a community which is ideally positioned to deliver fundamental and underpinning knowledge in key areas including, for example, how plants regulate carbon fixation, growth, nutrient uptake and source-sink relations in response to a host of biotic and abiotic stresses. The knowledge gained through such studies along with technology developments in genetic engineering, DNA sequencing and marker assisted breeding will allow translational opportunities in relevant crop systems to be explored more efficiently than ever before. Recent technology developments have also lowered the barrier to applying modern methods for the improvement of lesser-studied and wild plant species. This means that the target for translational research now is not just improvement of existing crops but rapid domestication of marginal and wild species.

Plant science needs cutting edge research to deliver its potential

The other very important output from the plant science community, that will play a crucial role in meeting the demand for greater and more varied agricultural productivity, is human resource. The availability of model systems such as Arabidopsis that enable breakthrough discoveries in biology and subsequent high-impact publications results in high-calibre young scientists being attracted to the field. We are now seeing many of these top-class scientists applying their knowledge and skills to the challenges outlined above. This is a crucial issue and one that must not be overlooked if we are to deliver on the potential that plant science has to offer.

Major Challenges for Plant Science

Break out groups at the workshop were tasked with defining the major challenges for plant science in the next decade. A series of consistent themes emerged which were embellished via round table discussions and a poster session. Seven major areas were defined:

Predictive Biology

In the last decade plant science has made spectacular progress in the identification of key genes that underpin the major processes of plant development and responses to the environment. This progress should continue and be augmented by advances in our understanding of gene regulation via transcription factors and by regulatory RNAs. However, the next decade will require the integration of these studies. In the real world it is not possible to separate developmental processes from those of environmental stress responses. Therefore a major challenge for plant biology is to combine the information known about specific processes into more global models with predictive value. This will require the development of new tools for quantifying biological processes and the application of a range of modelling techniques to create robust network models. This raises the issue of data storage, data availability and the availability of necessary software tools in a form that is easy to access by a wide range of non-expert researchers. The data and bioinformatic tools issue pervades all efforts in modern plant science and must be addressed in a coordinated manner. Finally such models will need to be extended beyond the laboratory to field environments to create plants capable of producing robust yields in the face of changing environmental conditions.

Understanding biology from the nano- to macroscale

Predictive modelling requires that accurate and quantifiable data are obtained at many levels of abstraction. At one extreme it will be necessary to understand the role of single protein molecules in regulating or carrying out key nodal events in regulatory and response networks. To achieve this many new technologies and analytical techniques will need to be developed. At the other extreme understanding of how the plant functions as a whole and as part of a community will be needed. Therefore, a major challenge for plant science in the next decade will be to understand the continuum of processes from the single molecule to the cell to the tissue and finally to the whole plant.

The role of time and space in biology

All biological processes are time and location dependent. Once more these concepts can be applied at the sub-cellular, cellular and whole organism level. A major challenge for plant biology is, therefore, to understand the role of time in altering plant responses and regulatory pathways. This can be at the level of cyclical changes brought on by the day/night cycle and by temporal changes influencing development over the growing season. Spatial data are needed in terms of the process location within cells or tissues, relationship of cell types to one another and to the environment in which the plant needs to grow. Developing the technologies to measure these issues and integrating the data into systems models will be a key challenge.

Evolution

The genomic footprint of evolution on plant genomes has much to reveal of fundamental and practical significance. Challenges will involve establishing the evolutionary constraints on system architecture and the discovery of new principals underlying evolution.

Crucial to these studies will be the development and understanding of the genetic and molecular mechanisms that generate organismal robustness and diversity. Here many issues involved in the interaction of plants with the biotic and abiotic environment that drive selective processes need to be understood. Tackling this challenge will generate a knowledge base of how to select from crops, wild plant species, or novel gene combinations to produce varieties that are able to withstand changing physical environments and pathogens.

Growth responses from the single cell to whole organism and their regulation

Understanding how a plant grows to achieve its final form remains a major goal for plant science. Specific topics to address include investigating how a cell grows, how the growth of the 'all important' cell wall is regulated and the nature and mechanisms of cell to cell communication, how tissue development is coordinated and how the mechanisms of tissue specific regulation of gene expression and the biomechanics of growth are achieved. Growth parameters alter organ shape and understanding the environmental and genetic regulation of such processes is important to translate information to crop production. To maximise yield potential understanding the control of resource allocation between shoot, root and seed will be of fundamental importance.

Principles of responses to the environment

As plants are sessile and unable to respond to threat with a flight response, obtaining a complete understanding of how plants respond to environmental change is a major challenge of plant science. In the abiotic environment important driving forces include drought, salt and light stress, consequences of geographical location and soil type. In the biotic environment responses to pathogens, insect pests and beneficial microbes will need to be fully understood. This work will require a deep understanding of genetic variation defining the environmental responses and the key regulatory networks used by plants in response to environmental stress.

Sustainability

Food prices are increasing worldwide making availability of sufficient nutrients a major issue to many people in Europe and worldwide. Combined with the increased demand for food is a changing environment where climatic patterns are less predictable. Consequently it is essential that the plant research community rises to the challenge of producing novel crop varieties that produce sustainable yields under many growing conditions. This challenge in many ways highlights the need for investment in plant science across the range of research from the fundamental to the applied. It will require the co-ordination of plant research to achieve this where Arabidopsis remains a driving force for cutting edge and translational research to inform a broad research base impacting on medical, plant, environmental and evolutionary science and to provide plant breeders with the knowledge and resources to achieve sustainable crop production.

Arabidopsis as a model system

Arabidopsis is the most widely used model system to study plant biology. Many of its advantages stem from the availability of genome information and the subsequent development of tools that can be applied in any laboratory. However, the invention of a new generation of technologies to analyze genomes has helped lower the barrier between model and non-model species, and led to discussion of whether concentrating resources on Arabidopsis research can still be justified. Therefore, a major topic for discussion was whether Arabidopsis is still an appropriate model system to meet the challenges facing plants described above.

The advantages of Arabidopsis were divided into:

1. Those that are inherent to Arabidopsis as a model system and are likely to persist over the longer term.
2. Those in which Arabidopsis can play a major role in development but that are more transient as they will eventually be replicated in other species to develop translational outputs.

Inherent Strengths

Many of the inherent strengths of Arabidopsis are those that contributed to its initial adoption as a model system. The small size of the adult plant and its simple growth requirements allow large populations to be grown without the need for extensive glasshouse or field space. Therefore many laboratories, that would otherwise be excluded from high-level plant research because of a lack of facilities, can contribute through working on Arabidopsis. Similarly, the short generation time of Arabidopsis of a few weeks accelerates genetic analysis and identification of mutants. This capacity to produce several generations a year enables rapid progress in genetic analysis of phenotypic traits, and the testing of hypotheses. The small genome size of 130 Mb makes molecular biology approaches simpler, reducing the proportion of repeat sequences and making the analysis of genes easier. The ease of introducing foreign DNA with Agrobacterium allows the generation of thousands of transformants and makes systematic analysis of gene function feasible. Finally, the wide geographic range of Arabidopsis allows the collection of accessions from very different environments enabling the study of natural genetic variation in accessions and populations. The small genome size of Arabidopsis facilitates analysis of whole genome sequences from literally hundreds of different accessions providing a complete description of the genetic variation within the species.

Extrinsic strengths

Arabidopsis researchers also benefit from an extensive set of tools and materials that are not yet available in other species. These so called extrinsic advantages may become available in other species through technological advances, but today still represent a significant benefit to those working in Arabidopsis. These advantages include a high quality genome sequence that has been more thoroughly annotated than that of any other plant species, and now includes detailed information on whole genome patterns of DNA methylation, histone modifications and small RNAs. The high-frequency transformation of Arabidopsis and the small genome size have allowed the precise mapping of over 300,000 T-DNA insertions and the recovery of insertions in 90% of genes. These resources are supplemented with mutations recovered from a wide range of forward genetic screens. Furthermore, Arabidopsis was the first plant species for which whole genome transcription profiling was available. The community organised concerted efforts to use these arrays to describe expression profiles at different developmental stages and under a wide range of different environments. Widely accessed databases are now available providing these data to researchers. Finally, the global community of laboratories working on Arabidopsis continues to generate information and tools at an ever increasing rate. The range and depth of information available allows connections to be made between different areas of plant research, and for hypotheses to be rapidly tested.

The overwhelming view of the participants at the workshop was that the combination of these inherent and extrinsic advantages of Arabidopsis still provides an extremely powerful system to answer fundamental problems of plant biology. The intrinsic advantages are as relevant today as they were when Arabidopsis was initially selected as a model system almost two decades ago, and will ensure that Arabidopsis endures as a model system. The depth and variety of the extrinsic advantages will not be duplicated in other plant species for many years. To cease development of the Arabidopsis model system would starve crop science of the flow of fundamental knowledge from which it has benefitted over the past twenty years and the analytical and predictive tools that can be developed via focussed community efforts on one system will not emerge. Nevertheless, the participants also stressed the need to develop other model systems in parallel with Arabidopsis, to study important traits not accessible in Arabidopsis such as C4 metabolism, wood formation, perennialism or symbiosis with Rhizobium or Mycorrhiza. A recurring theme from the workshop was that research in Arabidopsis must not be viewed as separate from the larger plant science community but rather as being an essential component. In the next decade it will be critical to develop close connections between researchers working on model and crop plants to ensure efficient transfer of discoveries made in Arabidopsis.

Role of Arabidopsis in achieving the Goals of Plant Science

From the major challenges listed above, several key scientific topics were identified for which *Arabidopsis* is uniquely suitable. These topics range from molecular and cell biology analysis of cellular and tissue function to understanding the nature of genetic variation and its role in evolution. A major emphasis in all the research areas is the development and use of quantitative data analysis techniques to enable predictive biology. This will be central to the role of Arabidopsis in plant science over the next 10 years, resulting in predictive modelling of selected cellular processes and signalling networks.

Plant transcriptional code

The transcriptional code in plants is only poorly understood. Therefore, the combinatorial relationship between the binding of transcription factors to DNA and the resulting production of RNA at the correct time, in the correct cells and to the correct amount demands further investigation. The challenge is to understand in detail the control of RNA expression of all genes in time and space at cellular resolution and in response to changing environmental conditions. Parameterising the interaction of transcription factors with their DNA targets and the protein complexes that form at promoter structures will form a key component of these studies. This knowledge will provide the molecular basis for an understanding of most of the other intra- and intercellular processes discussed below.

Evolution

A prerequisite for understanding plant development and adaptation to the environment in rapid and evolutionary timescales is an improved knowledge of how genetic information accumulates, is maintained and modified. Key questions that could be tackled in Arabidopsis include; the importance and consequences of genome rearrangements, how new gene functions are acquired, the significance of genetic interactions and the role of epigenetic control of gene function. Combined with an understanding of the transcriptional code these studies will lead to an understanding of the dynamic changes at the genome level that result in evolution of diversity.

Protein function

The molecular details of protein function are still poorly understood and the structure of the vast majority of plant proteins is not known. However, without this basic information functional properties of proteins cannot be predicted. Plants often contain families of highly related proteins that exhibit functional redundancy and a major challenge is to be able to accurately predict their role. In addition, data increasingly indicate that plant proteins possess multifunctional properties depending on their cellular environment and intracellular localisation. Arabidopsis will play a major role in elucidating structure function relationships in plant proteins in the next decade.

Translational and post-translational regulation

Understanding transcriptional regulation alone will be insufficient to fully parameterise gene regulatory networks. It will be essential to understand the mechanisms and the significance of translational and post-translational protein modification in network regulation. These mechanisms may include differential protein synthesis and turnover, *in vivo* dynamics of protein distribution in the plant cell and *in vivo* dynamics of protein complex formation and the complex endomembrane system. The quantitative parameters of these cellular regulatory principles will provide important knowledge of how the activity of multi-enzymatic metabolic pathways and regulatory networks are established, maintained and modified within the plant cell. This information is of great importance to understand the phenomenon of how a single plant cell is able to deal with the information influx of multiple signals, to perform their integration and to translate it into a meaningful and specific output such as cell growth and differentiation or reprogramming of cellular metabolism.

Cellular communication

Communication between plant cells via the plasmodesmata and plasmamembrane-located surface receptors is essential for the exchange of information monitoring the microenvironment. In addition, cell to cell communication is indispensable for cell specification and differentiation in the meristematic stem cell niches, which determine plant architecture. Although a huge number of proposed cell surface receptor genes are known in plants, their potential role in cell-cell communication (and other cellular processes) is enigmatic. In addition, the regulatory function of the plasmodesmata in cell-cell communication is poorly understood. Thus, there is a major backlog in even basic knowledge on the degree, significance, molecular determinants and specific regulation of the plant cells' communication. This deficit is more regrettable as cell to cell communication may play a significant role in tissue-wide processing of systemic signals, which coordinate whole plant responses.

Coping with environmental stress

Coping with a constantly changing and complex biotic and abiotic environment is a major challenge for plants. It is, therefore, not surprising that plants respond in a complex spatio-temporal manner to changing environmental conditions. The responses of the plant can be expressed on many levels, including gene expression, protein regulation and metabolism. The quantitative outcome of these responses is the result of the activity of complex multigenic networks. Thus, the plant´s responses to the environment are seen as multigenic traits and result from genetic variation and selection during evolution. However, we understand little about how plants cope with a multitude of environmental signals in a competitive environment and how the genotype and complex genetic interactions determine the execution of the appropriate responses and the generation of an adapted phenotype. Furthermore, we need to understand how genetic variation within and between species contributes to creating robustness to environmental stress using ecological tools.

Creation of validated models of regulatory networks will enable rational plant engineering, via genetic selection or synthetic biology techniques, to produce crop plants able to produce sustainable yields in the face of a changing climate.

Workshop Recommendations

1. Global food security and the need to develop sustainable and environmentally friendly biorenewable feedstocks to replace fossil fuels will inform strategic thinking in plant research in the next 10 years. For plant science this will require a two-pronged approach with strong investment in Arabidopsis research, to generate fundamental knowledge as well as novel technologies, and in crop plant research to deliver translational outputs.

2. During the last 10 years Arabidopsis has underpinned the development and application of genomics technologies in plant science. Many of the genes and techniques being used in the crop sector were developed first in Arabidopsis. Development of the next generation of approaches, such as systems and synthetic biology, in Arabidopsis and other models will continue to play a major role in the translation of basic research to practical outcomes. Arabidopsis research, therefore, should be viewed as an essential component of a continuum of plant science research from the fundamental to the applied. Other plant model systems will also be required to study traits not accessible in Arabidopsis.

3. In the next decade, biology will change from a descriptive to a predictive science. Arabidopsis has a central role to play in this transition in the plant sciences. It is the major plant platform in which the development of quantitative techniques necessary to produce predictive systems models is feasible. Model generation and testing will be critical in the next phase of translational research; as key components of these models become targets for selective breeding programmes focused on major world problems such as food security and environmental change.

4. An essential component of future success will be the maintenance of a productive and collaborative plant science community that consists of both basic and applied research. Ongoing community building activities at the national and international level should therefore be encouraged and supported. Successful examples of such interactions include MASC (Multinational Arabidopsis Steering Committee - International) and GARNet (Genomic Arabidopsis Research Network - UK), at the coordination level and AFGN (Arabidopsis Functional Genomics Network – Germany) and ERA-PG (ERANET in Plant Genomics - EC) in generating fundamental and translational research.

5. Publicly-accessible data are critical to the advancement of plant research and promotion of data sharing is needed. We must ensure the security of our major data and resource repositories such as TAIR and stock centers and support timely sharing of resources. Sufficient repositories for current and future datasets and resources must be available.

6. High impact discoveries in Arabidopsis, along with an increasing moral imperative to find answers to current global problems, will play an important role in attracting and developing highly-trained researchers in the plant sciences who can apply their knowledge and skills in the agricultural sector as well as other areas of plant biology. Integrating advanced techniques and approaches with current and future datasets will continue to attract high-quality interdisciplinary researchers.

Appendix 1

Workshop Programme

EU 2020 Vision for Plant Science

BBSRC and DFG Sponsored Workshop

2-3 June (Haus der Begegnung, Mandelbaumweg, Bonn Bad Godesberg)

Programme

<u>Monday 2nd June</u>

13:30 - 14:00 Welcome and workshop outline

14:00 - 15:15 Accomplishments and lessons learned from Arabidopsis functional genomics research in Europe (2000-2010)

15:15 - 15:45 Coffee Break

15:45 - 16:35 2020 Vision for Plant Science

16:35 - 16:45 Break

16:45 - 17:45 2020 Vision for Plant Science continued

17:45 - 18:00 Break

18:00 - 19:00 2020 Vision for Plant Science continued

19:00 - 20:00 Dinner

20:00 - 21:00 Informal Discussions

<u>Tuesday 3rd June</u>

8:30 - 9:00 Recap of Workshop

9:00 - 10:30 Future prospects for Plant Science in Europe

10:30 - 11:00 Coffee Break

11:00 - 12:30 Future funding prospects for research on model plants

12:30 - 13:30 Lunch

13:30 - 16:00 Summary and Conclusions

Appendix 2

Workshop Participants

Philip Benfey, USA
Jim Beynon, UK
Atle M. Bones, Norway
Francois Buscot, Germany
Danny Chamovitz, Israel
George Coupland, Germany
Christian Fankhauser, Switzerland
Ulf-Ingo Flugge, Germany
Ian Graham, UK
Claire Grierson, UK
Klaus Harter, Germany
Marie-Theres Hauser, Austria
Pierre Hilson, Belgium
Heribert Hirt, France
Gerd Jurgens, Germany
Regine Kahmann, Germany
Michael Lenhard, UK
Keith Lindsey, UK
Sean May, UK
Dierk Scheel, Germany
Arp Schnittger, France
Willem Stiekema, The Netherlands
Mark Stitt, Germany
Miltos Tsiantis, UK
Francois Tardieu, France
Pablo Vera, Spain
Alex Webb, UK
Peter Westhoff, Germany

Observers
Ruth Bastow – GARNet/BBSRC
Christine Bunthof - NGI
Parag Chitnis - NSF
Joanna Friesner - MASC
Joanna Jenkinson - BBSRC
Catherine Kistner - DFG
Patricia Schmitz-Muller - DFG