Supporting Information: Notes on questions A11. – E17.

A. **Society**

For questions **A1. -A10**. see the main text.

A11. How can we translate our knowledge of plant science into food security?

The security of food supplies is a social, economic and political issue as well as an agronomic problem. Plant science can contribute to food security by providing the knowledge and expertise that will be required to produce food on marginal lands and increase the efficiency of food production on existing land. Insights from plant science into nutrient and water use efficiency, salt tolerance, yield optimisation, pollination, and post-harvest physiology (to optimise shelf life during food distribution) will all be important. Another possible contribution is through the domestication of plant species that have not previously been grown for food. Meeting this agenda will require excellent translation of existing knowledge and approaches to a wide range of plant species, as well as research on food plant species themselves.

A12. Which plants have the greatest potential for use as biofuels with the least affects on biodiversity, carbon footprints and food security?

There are a variety of traditional food crops that can be used for biofuel production, such as oilseed rape, maize (*Zea mays*), sugar cane (*Saccharum* spp.), and also dedicated bioenergy crops, such as *Miscanthus*. *Agave* spp. can be highly productive with limited rainfall. Although there are issues surrounding the use of food crops (1st generation) for energy (the food vs. fuel debate), much research effort is being put into 2nd generation (non-food crops) and 3rd generation (algae fuel) dedicated bioenergy crops, which have better energy balances and do not compete for land with food production. In addition to selection of useful plant species, being able to harness the energy provided by plants more efficiently through a variety of breeding programs, as well as improvements in conversion technologies, will be equally important as this will allow us to achieve the same yields from smaller areas of land. Other issues that impact yield also need to be considered such as improvements in site preparation, weed elimination and increased crop resistance to pests and disease. Efficient crop management will also help dedicated bioenergy crops to grow on marginal and idle land. The effects of crops grown for biofuels on biodiversity will depend on the extent of land use change represented by biofuel production. Some dedicated bioenergy crops have been found to enhance resources for biodiversity.

A13. Can crop production move away from being dependent on oil-based technologies?

Agriculture currently relies hugely on oil for field machinery operation, the production of fertilisers and pesticides, crop drying and transport. As peak oil production is reached and oil supplies begin to decline there will clearly need to be a re-evaluation if production is to be maintained or even increased to meet future population demands. The solution is likely to involve sustainable energy, much more efficient production and use of fertilisers and fresh water, and better pest and pathogen control.

A14. How can we use plant science to prevent malnutrition?

Malnutrition literally means bad nourishment caused by not enough or the wrong type of food. It is caused by a clinically inadequate or excess amount of proteins, energy and micronutrients such as vitamins. Plant science can help create low-cost, nutritionally complete foods by translating knowledge from the lab into the farmer's field. The use of genetic modification is particularly promising as it can produce plants with enhanced levels of protein and/or vitamins, as is the case for the so-called "golden rice". "Golden rice" was genetically engineered to express a gene from a daffodil, which resulted in the production of ProVitamin A in the rice, thus helping address blindness and death in malnourished children. As well as improving the nutritional quality of plants, plant science can help by increasing plant productivity and thus making food more widely and economically available to malnourished people.

A15. How can we use knowledge of plants and their properties to improve human health?

Obtaining the requisite nutrients is central to human health and longevity, but many of our current plant based food species are less than perfect from the point of view of human nutrition. Improvement in agricultural practices can only marginally increase the nutritional value of our crops. Instead we require a greater understanding of plant processes so that we can engineer crops with enhanced nutritional value such as elevated mineral content, improved fatty acid composition and increased amino acid levels. It is also important that healthy foods are palatable as this is likely to improve diets. Plants not only supply us with nutrients but many existing medicines are also plant derived and there are certainly more still to be found. There is also the possibility that plants could be used as 'factories' for the production of some pharmaceuticals by introducing or modifying biosynthetic pathways.

A16. How do plants and plant communities (morphology, colour, fragrance, sound, taste etc.) affect human well being?

In addition to providing the essential human needs of food, fibre and energy, plants have an important impact on human well being. There is evidence that the mere presence of plants can elicit beneficial physiological and psychological responses in humans, including restoration from stress and cognitive fatigue, accelerated recovery from illness, and improved social cohesion, and the value that humans place on the aesthetic properties of plants sustains the gardening and floral industries. A sound scientific understanding of the basis of the interactions between humans, plants and environment is needed to ensure that society recognises the true value of plant life and benefits fully from it.

A17. How can we use plants and plant science to improve the urban environment?

In urban environments plants can improve air quality, provide cooling and shade, reduce risk of flooding, and offer insulation against noise as well as providing attractive green space. Green roofs and green walls provide new ways of introducing more plants into our towns and cities but represent very different horticultural challenges compared to traditional parks and gardens. Our knowledge of the best plants to choose for these new environments, and our understanding of how to get the most from them, needs considerable development if we are to harness the power of plants for sustainable cities.

A18. How do we encourage and enable the interdisciplinarity that is necessary to achieve the UN's Millennium Development Goals that address poverty and the environment?

The United Nations has set a series of goals, termed the UN Millennium Development Goals (http://www.un.org/millenniumgoals/), to address improvements in the human condition, and that are to be achieved by 2015. These goals are to: eradicate poverty and extreme hunger, achieve universal primary education, promote gender equality and empower women, reduce child mortality, improve maternal health, combat HIV/AIDS, malaria and other diseases, ensure environmental stability and develop a global partnership for development. Plant science has a key role to play in both addressing the elimination of extreme hunger and in ensuring environmental stability, but the communities of scientists working on these two areas rarely interact. Enabling true interdisciplinarity to address multi-pronged questions will be key to finding solutions that are mutually acceptable.

B. Environment and Adaptation

B1. How can we test if a trait is adaptive?

A trait is a distinguishable feature, characteristic, quality or phenotypic attribute of an organism. Adaptive traits are those that increase the probability of an offspring of an organism surviving and reproducing if they are inherited. Traits are not necessarily adaptive for all time; for example, a currently valuable trait, such a cold tolerance, might lose its value in a warming climate. Also, basic plant science research tends to focus on identifying and understanding biological mechanisms. To do this we need to compare very precise growth conditions with highly defined changes and we tend to look at only one or two changes in conditions at a time. In contrast, genuinely adaptive traits might have more subtle or multifaceted effects that might only confer adaptive advantages under more realistic combinations of selection pressure. Identifying adaptively important genes is more difficult in some species than others; for, example, in trees this is a particular challenge because of their long generation time but genomic approaches, such as association mapping, may help us to succeed in the future.

B2. What is the role of epigenetic processes in modulating response to the environment during the life span of an individual?

The elegant simplicity of early descriptions of bacterial gene regulation suggested models in which organisms interact with their environment using simple receptors that can interact directly with the DNA sequence and the transcription machinery. The chromatin that forms the chromosomal environment of plant DNA provides an additional layer of regulation for the expression of specific genes during a plant's lifespan. Modifications of histone proteins, or of the DNA itself (without changing the coding sequence) can activate or repress a gene or chromosomal region, and play important roles in a number of processes, including the control of flowering. The detailed relationship between these epigenetic effects and the better understood mechanisms of transcriptional regulation by DNA-binding proteins and RNA polymerases is not clear. The extent to which epigenetic effects modulate plant morphogenesis has yet to be established and it is likely that epigenetic processes play a central role in the plant life cycle. Further understanding of these processes will help us determine the extent to which plant development is pre-programmed as opposed to environmentally shaped.

B3. Are there untapped potential benefits to developing perennial forms of currently annual crops?

Why don’t we have perennial varieties of many of our most important crops that need not be replanted every year? There are in most cases close relatives of these plants that are perennial, so it is likely that we could develop such crops. Perennial forms of some crops, such as potatoes and tobacco (*Nicotiana*), already exist but the most highly productive forms can be treated as annuals. Perennial plants always save resources in their roots so that they have reserves for the following season, and they are more likely to forego reproduction if weather conditions are poor because if they can make it through a crisis alive then there is a chance to reproduce the following season, whereas annuals commit all their resources to reproduction in the current season. One of the almost certain outcomes of breeding a perennial crop is lower production because a portion of the resources will be held back by the plants for the following season. This makes perennials less attractive as crops; we are too focused on short term production to allow the plants we grow to retain products of their photosynthesis for subsequent years. If this lower productivity were compensated by lower costs associated with tillage and planting, then such crops would become feasible. As the cost of fertilizers and fuel continue to rise the balance might be tipped towards the use of perennials in agriculture.

B4. Can we generate a step change in C_3 crop yield through incorporation of a C_4 or intermediate C_3/C_4 or CAM mechanism?

C_4 plants have a competitive advantage over C_3 plants under conditions of high temperature and water shortage. It has been calculated that C_4 plants only use one third the number of water molecules used by C_3 plants to fix one molecule of CO_2. They achieve this by spatial separation of the site of CO_2 uptake from the site of photosynthesis, and have evolved specific anatomical and biochemical features to achieve this. Members of the Crassulaceae (succulents), adapted to grow in arid regions, use a variation called Crassulacean Acid Metabolism (CAM), where they temporally separate CO_2 fixation from photosynthesis. This enables them to conserve water by taking up CO_2 at night, when their stomata remain open, and carry out photosynthesis during the day, when their stomata are shut.

C_4 and CAM photosynthesis have arisen on numerous separate occasions during evolution. Some crops, such as maize, are C_4, but many, such as wheat, are C_3, and pineapple has CAM. There are plants that operate C_3 or CAM, depending on the environmental conditions, and some C_4 plants lack the special anatomical features normally associated with C_4. This suggests that it may be possible to introduce some C_4 or CAM features into more crop plants, making them more efficient at CO_2 fixation and able to flourish while using less water.

B5. How do plants regulate the proportions of storage reserves laid down in various plant parts?

Different plants produce nutritious roots, stems, rhizomes, tubers, leaves, flowers, pods, seeds, and fruits, either to store food reserves during a period of restricted growth or dormancy, or to attract animals to aid in seed dispersal. Farmers have carried out selective breeding of important crops over thousands of years to provide increased yields, and improve quality and reliability of production.

Different plants provide different types of product, for example the main constituent in potatoes (*Solanum tuberosum*) is starch, seeds provide protein, minerals and sometimes oil, and leaves and fruits are rich in some vitamins. Understanding what determines the type and quantity of chemical constituents accumulated and stored in a developing organ is important for the agricultural and food industries and is of particular importance in regions liable to food shortages or restricted choice of products. The amount of a constituent can be influenced by the growing environment, or the species or variety, and by genetic and biochemical controls. Improved understanding of these processes should enable the breeding of new crops and varieties and improve the productivity, quality, and nutritional value of plants.

B6. What is the theoretical limit of productivity of crops and what are the major factors preventing this being realised?

The yields of major agricultural crops in most regions have risen significantly in recent years, with improvements in plant breeding, crop protection, crop nutrition and cultivation practices all playing a part. However, there are indications that some crops (for example wheat yields in the UK according to 1997 - 2007 production figures) may have reached a plateau. What has caused this effect? In trying to address this problem it would be very useful to explore theoretical limits of productivity. Such research could enable us to identify not only limiting factors in crops where progress has slowed, but also untapped potential in other crops where development efforts have been less focused.

B7. What determines seed longevity and dormancy?

Some seeds die after a week or two, whereas others can survive for tens of thousands of years. Also, many seeds, even though they are alive, do not germinate even when the conditions are ideal; instead they remain dormant and germinate on another suitable occasion. These processes help the plant to survive by increasing the number of opportunities for progeny to grow successfully; if all the seeds germinated at the same time they might all be killed simultaneously by the same event, whereas if some of them delay germination to a time after this adverse event they will have increased their chance of survival. However, these mechanisms cause problems for agriculture, which requires crops to germinate all at once and in a defined window, so that that they can be harvested together. Simultaneous germination also allows us to get rid of unwanted plants (weeds) easily. As many of our staple foods are un-germinated seeds (e.g. wheat and rice, *Oryza*, grains) we suffer significant crop losses when these germinate too early, which is known as pre-harvest sprouting. Understanding how seed longevity and dormancy are controlled will help us to control germination so that we can prevent crop losses, improve weed control and optimise crop production.

B8. How can we control flowering time?

The triggering of flowering is a highly regulated process and, depending on the plant, is influenced by many interacting pathways and environmental influences (light, temperature and so on). Extensive research has revealed many of the mechanisms that control this, especially in the model plant Arabidopsis. An even more complete understanding of the processes is needed in major cultivated species, where the ability to fine-tune flowering to the growing season could give significant advantages for both breeders (easier production of hybrids, and faster breeding cycles) and producers (timing of flowering better adapted to specific environments).

B9. How does signalling and cross talk between the different plant hormones operate?

Plant hormones play an essential role in the control of growth, development and reproduction, and are important for processes affecting food production, quality and adaptation of plants to the environment. There are relatively few hormones, although new ones are still being discovered. Each hormone influences many different processes, and seems to have its own receptor(s) and dedicated components in signal transduction chains, but there is growing evidence for branching of some signalling chains and interactions (cross-talk) between different signalling pathways. It may be that receptors interact directly or indirectly, or that some molecular components act in two or more signalling pathways, or effects of one signalling pathway can feed back and influence other signalling pathways. Thus it seems that hormone signalling is an interacting signalling net or web. Resolving this web and its interactions with other signalling pathways is the key to understanding the control of plant development and responses to the environment.

B10. Can we develop salt/heavy metal/drought tolerant crops without creating invasive plants?

Ever increasing areas of land are being degraded and removed from agricultural use, whilst at the same time population growth, changes in diet, and the need for renewable energy are increasing the demand for agricultural land. Improved tolerance of salt or heavy metals would therefore be a great benefit for crop production and soil remediation. Drought tolerance has always been a desirable attribute for many areas of the world and this is only likely to increase with the effects of climate change. However, there is evidence that many plants with tolerance to these abiotic stresses are potentially invasive, having a competitive advantage over less tolerant species or varieties, including the native flora. There has been very limited invasion risk assessment carried out by plant breeders to date. There is a need for crops which will excel in the cultivated environment for which they have been selected but which are unlikely to establish and spread in non-cultivated environments.

B11. Can plants be better utilised for large-scale remediation and reclamation efforts on degraded and/or toxic lands?

There is considerable interest throughout the world in remediation and reclamation of contaminated or degraded land using plants, often called phytoremediation. Phytoremediation works in a number of different ways, depending on the contaminant and the plant. For example, some plants extract heavy metals into harvestable roots and shoots. In salt deserts, it has been proposed that salt-tolerant native grasses could be used to improve the land. Phytoremediation is considered to be a clean, cost effective and non-disruptive mechanism compared to other solutions such as excavation. Although phytoremediation technology is currently being utilised, there is room for improvement; for example, many of the available plants are slow growing and this leads to clean-up rates that are slower than those using more conventional, but less environmentally friendly, methods.

B12. How can we translate/exploit our knowledge of plants and ecosystems into "clever farming" practices?

One of the major issues facing us today is how to feed a growing population in a sustainable manner. The conventional view is that intensive farming is more productive yet more environmentally damaging than extensive agriculture. Biological research can help to increase the efficiency and sustainability of crop and animal production. For example advances in plant science will allow us to develop and/or manage crops which can better defend themselves against pests and diseases as well as coping with the stresses of climate change. Understanding how plants utilise resources for processes such as growth, reproduction and defence will allow us to increase productivity. The importance of biodiversity in agriculture has been accepted for some time, and research is now focussing on the provision of a range of ecosystem services (e.g. clean air and water, pollination, decomposition of waste). We will need to integrate all relevant knowledge and skills, including risk management, to develop "clever farming" systems that are productive, sustainable and allows ecosystem services to flourish.

B13. Can alternatives to monoculture be found without compromising yields?

Monoculture is the practice of growing a single crop over a wide area. For example, in the UK a farmer may choose to grow one or a few cultivars of wheat on over half of the cultivated area. Uniformity reduces inter plant competition and allows standardisation of the agronomy. The result is high yields and greater efficiency. However there is evidence that monoculture reduces biodiversity, increases the risk of pests and diseases and leads to loss of soil fertility. For many crops, the alternatives to monoculture that have been explored to date result in more expensive produce because the crops are lower yielding and/or the labour costs are higher. Whereas growing mixtures of species can be problematic in modern agricultural systems, growing mixtures of varieties may be more feasible in some situations and is this being actively explored for some crops, for example wheat and barley (*Hordeum* spp.).

B14. Can plants be bred to overcome dry land salinity or even reverse it?

The loss of farm and grazing land because of rising salt levels is a huge concern for countries such as Australia. Vast amounts of salt have accumulated underground over many thousands of years from the weathering of rocks or from sea salt dropping as rain. Native vegetation evolved to deal with these conditions by becoming relatively salt-tolerant with deep roots and a high demand for water. However, the introduction of arable and pasture crops which have shorter roots and lower water demands has resulted in less rain fall being absorbed, causing a rise in the water table level and along with it salt is being brought to the soil surface and creating desert like conditions in which even the native vegetation cannot grow. The problem is so serious that many believe that it will not be possible to recover some areas. The challenge is therefore to breed and introduce new crops, and to develop new land uses which provide less of a water imbalance.

B15. Can we develop crops that are more resilient to climate fluctuation without yield loss?

Long periods of selection mean that most of the world's major crop species are generally well adapted to the climates in which they are grown. However, a rapid period of climate change, as predicted by some of the Global Warming models, would result in a number of the crops we grow today no longer being suited to the environments they find themselves in, resulting in vast yield losses. For example climate fluctuations could result in insufficient drought or water-logging tolerance in some crops or even cause inappropriate metabolic activity – the 'C_4' photosynthetic pathway is more efficient in warmer environments than the 'C_3' pathway that is common in temperate crop species. Changes to the climate could also allow 'new' pests or pathogens to thrive causing crop devastation. Dealing with this challenge will involve a greater understanding of how plants respond and adapt to changes in climate, allowing us to transfer useful traits to crops of economic value or domesticate new species that are better adapted to deal with climate fluctuations.

B16. Can we understand (explain and predict) the succession of plant species in any habitat, and crop varieties in any location, under climate change?

Change in the species composition is a natural phenomenon, and has gone on throughout evolutionary history. These changes, including those that occur with crop varieties, are relatively easy to show after the fact. The challenge is to explain why particular changes have happened in a variety of circumstances, and whether these changes have common cause. Predicting change in simple environments is challenging, but making these predictions in realistic, complex situations under a variety of scenarios of environmental change will help us not only use plant diversity to benefit our own species, but conserve the genetic base for plant evolution for the future.

B17. To what extent are the stress responses of cultivated plants appropriate for current and future environments?

Plant breeding often takes place in a specific environment and the resulting cultivars may perform well (e.g. be high yielding and/or have certain quality characteristics) under those specific conditions while not having the resilience to produce optimum performance when grown elsewhere, where factors such as temperature and water availability may be significantly different. Current selection methods risk narrowing the diverse gene pool required to meet the challenges that the future will bring. Research is required to identify effective ways to address this.

B18. Are endogenous plant adaption mechanisms enough to keep up with the pace of man-made environmental change

The global climate is rapidly changing as a result of mankind's actions. Most plants are incredibly adaptable, but each species has its own preferred climatic range. Are our familiar wild and crop species sufficiently adaptable to stay within their existing ranges and, if not, how are these most likely to change? We know that factors such as carbon dioxide concentration, temperature and humidity have important effects on plants but what are the best ways of monitoring the situation, what is the most useful knowledge to have about plant responses and how can this knowledge be usefully applied?

B19. How can we improve our cultivated plants to make better use of finite resources?

The world needs to produce more food, fuel and fibre from plants with increasingly limited resources. In many cases land does not naturally contain sufficient nutrients and water to sustain crop production. Traditionally, this has been overcome by applying fertilisers and water, but a large proportion of the fertiliser and water that are applied are not taken up by crops. The production of some fertilisers, especially nitrogen, can consume huge amounts of energy and has significant carbon costs. Also, excess fertiliser that is not taken up by crops can leach into the environment and cause environmental damage. Fresh water supplies are increasingly scarce, and in the future we will not be able to afford to waste them. It should be possible to reduce fertiliser and water waste by selectively breeding plants that are better at taking up nutrients and water from the environment, and storing, moving, and using them within the plant. At the moment we do not understand plant processes sufficiently to do this in a predictable, reliable way. Potential benefits from increasing our knowledge include reduced pollution from excess fertiliser in field run-off, reduced carbon costs of fertilisers and irrigation, increased crop productivity, and the potential to bring marginal lands with low nutrient and water availability into crop production. To be truly sustainable, this should be achieved whilst maintaining nutrient stores and nutrient cycles upon which the broader environment depends.

B20. How do we grow plants in marginal environments without encouraging invasiveness?

Marginal habitats (which can support only a few species or individuals) are among the only land areas available for the spread of agriculture and human population that will not entail massive loss of biodiversity. New crops for these areas are important for helping to feed, fuel and clothe the human population, but such crops are bred for tolerance of environmental stress, bringing along aggressive survival and reproductive characteristics. These characteristics can cause them to become invasive weeds that can cause environmental damage beyond intended sites of cultivation. Invasive plant species reduce bio-diversity and habitats, endanger indigenous species and are a threat to food security via the reduction of crop yields. They can be major contributors to environmental degradation. Just what causes plants to become invasive is not well understood, and it is not clear that invasiveness is retained as plants become integrated into local environments. Some traits clearly pre-dispose a species to invasiveness, for example Japanese Knotweed *Fallopia japonica* (now a major problem) is tolerant of a wide range of soil types and pH ranges, has a resilient root structure, from which it is able to re-grow quickly and its growth habit rapidly smothers other species. Coupling a deeper and more sophisticated understanding of invasiveness with an understanding of how to breed crops for use in marginal environments will help to feed populations where hunger is a problem whilst minimising environmental damage.

B21. How can we use the growing of crops to limit deserts spreading?

The advance of deserts (desertification) is a problem not only for the people who live on their margins, but for the availability of land for agriculture in many developing economies; Kazhakstan, for example, has lost half of its arable land over the last 30 years and the Gobi Desert is coming ever closer to Beijing. Desertification is occurring on most continents and is thought to be largely the result of man-made effects such as over-grazing and fire, but it is also due to increasing salt content of the soil and climate change. Plants can be used to stabilise dunes and to combat the increase in aridity that is a part of desert spread. The breeding of new crops that are extremely drought and salt tolerant, and have architectural and other properties that can help combat soil erosion, could help to hold back the spread of deserts into previously cultivated land. Developing crops that can do this whilst providing nutrition to local populations and livelihoods to local communities could be challenging, especially in a rapidly changing environment.

C. Species Interactions

C1. What are the best ways to control invasive species including plants, pests and pathogens?

Invasive species are an increasingly significant threat to our environment, economy, health and well-being. Most are non-indigenous (evolved elsewhere and accidentally introduced) and have been removed from the constraints which were regulating their growth in their native country/habitat. The best method of control is to prevent establishment in the first place or to quickly identify establishment and adopt an eradication programme. However if an invasive species becomes established many of the options for removal can cause environmental damage for example chemical control or mechanical excavation. Biological control (introduction of a natural predator/pathogen) can work well as long as the control organism targets the invasive species. Otherwise there is a risk that the control organism might also become an invasive species. Alternatives, such as manipulating existing natural enemies and/or the environment to enhance biological control, are also being developed.

Sustainable solutions are required if we are to deal with the continually growing problem of invasive species.

C2. Can we provide a solution to intractable plant pest problems in order to meet increasingly stringent pesticide restrictions?

Effective pest management systems will be key to ensuring we can generate a sufficient food supply in future years. Modern agriculture relies upon pesticides to limit the effects of pests. Current legislation at the national and international level will limit and in some cases ban the use of certain pesticides that have been shown to have adverse effects on human health or the environment, or can be replaced with safer/non chemical alternatives. For example slugs are mainly controlled using pellets containing metaldehyde, combined with agronomic measures, but a recent desktop study in the UK showed that these pose a greater risk to water quality than previously realised and unless the application of pellets is managed better they could be banned. There is no known resistance to slugs in many susceptible crops, such as oilseed rape (also known as canola, *Brassica napus*), and similar scenarios exist for many other pests and crops. Novel approaches to pest control are therefore urgently needed to help provide the next generation of safer and cleaner pest management systems.

C3. Is it desirable to eliminate all pests and diseases in cultivated plants?

Pests and diseases account for a large proportion of crop loss every year worldwide. The organisms that are pests and diseases in crops are, however, components of natural ecosystems, where they usually exist in balance with their hosts and their own pests and diseases. Complete elimination of all pests and diseases in our crops would, on the face of it, seem a good idea, but would be likely to cause unforeseen environmental damage. The degree to which a balance can be struck between crop productivity and the loss of organisms from the ecosystem needs to be explored and will depend on ecologically and evolutionarily smart plant breeding.

C4. What is the most sustainable way to control weeds?

A weed can be regarded as any plant existing in an area where its presence is 'undesirable'. In agricultural systems weeds can negatively impact both productivity and quality. For example in an arable crop weeds can cause yield losses via direct competition for resources, harvesting problems linked to the weed biomass and finally contamination of the harvested crop with weed seeds.

Previously effective methods of weed control such as stubble burning or the use of herbicides with high persistence or high general toxicity are no longer allowed due to the environmental damage they cause. Although modern chemicals are also highly effective, herbicide resistance has become a major problem and it is becoming increasingly difficult to control some groups of weeds in arable systems. There is also increasing concern about the persistence of some herbicides in water, affecting the ecosystem and increasing the cost of producing clean drinking water. In many countries, integrated systems are being advocated, including agronomic as well as chemical control methods and for some crops, herbicide resistance is now available providing another opportunity for control. However, weeds continue to be a major threat to crop production and new methods will be needed to help combat the negative effects of weeds.

C5. How can we simultaneously eradicate hunger and conserve biodiversity?

Eliminating human hunger requires food production and distribution to reach everyone on the planet. Currently food is very unevenly distributed, with some regions suffering constant shortages. One solution to this might be to simply increase the area of land under cultivation, but this brings a massive environmental cost with the loss of biological diversity in areas converted from natural habitat to farmland. Conservation of biodiversity, however, is not simple either, and the balance between these two key determinants of human futures must take into account many factors often not addressed when looking at one issue or the other. Here, interdisciplinarity and communication between communities of plant scientists will be the key to success.

C6. How can we move nitrogen-fixing symbioses into non-legumes?

Nitrogen is an essential macronutrient for plant growth and reproduction. Although nitrogen is an abundant element on the earth, and around 78% of the earth's atmosphere is nitrogen gas, most plants cannot fix nitrogen from the atmosphere. Instead they need nitrogen to either be supplied in the form of nitrate or ammonia which is usually limited in soils. Modern agriculture overcomes this problem by adding nitrogen to crop plants in the form of fertilisers. This practice is essential to sustain global food production, but the synthesis and application of inorganic fertilisers comes at high environmental and economic costs. Legumes are unique in the plant world as they are able to fix their own nitrogen via a symbiotic relationship involving *Rhizobium* bacteria. If we could induce non-legumes to enter into similar beneficial symbiosis it would reduce/eliminate the use of fertilisers.

C7. Why is symbiotic nitrogen fixation restricted to relatively few plant species?

Nitrogen is an essential element of life and plants must capture it from their surrounding environment. The availability of nitrogen is often a limiting factor for plant growth and some species of plants have overcome this limitation through beneficial interactions with nitrogen fixing bacteria, which can capture nitrogen from the air and turn it into plant food. However, the majority of plant species do not enter such interactions. It is important and potentially useful to define what allows certain species to undertake these symbioses and this may facilitate the transfer of this process to crop plants that are not capable of this nitrogen-fixing symbiosis.

C8. How can the association of plants and mycorrhizal fungi be improved or extended toward better plant and ecosystem health.

The majority of plants enter beneficial interactions with mycorrhizal fungi that help the plant in the uptake of essential nutrients from the soil. Such mycorrhizal interactions contribute significantly to healthy ecosystems and plant growth. Mycorrhizal interactions can likely be better utilised in agriculture to enhance sustainable farming practices. Current farming practices involve extensive land tillage that destroys the delicate fungal networks that contribute to mycorrhizal interactions. Reducing agricultural tillage may enhance mycorrhizal colonisation of crop plants. However, alternative methods may be possible such as enhancing the rate and extent of fungal colonisation of crop species.

C9. How do plants communicate with each other?

Whilst plants can't communicate via sound, they can use other signalling modalities such as olfaction. When damaged, plants produce a blend of volatile organic compounds, which not only communicate to other plants of that species, but also to a range of animal species in the surrounding ecosystem. These volatile signals can prime neighbouring plants to up-regulate their defence pathways as well as helping defend the affected plant directly (warning smell) and indirectly (SOS signal detected by parasite/predator of the herbivore damaging the plant). A number of volatile elicitors (e.g. cis-jasmone) have now been identified and used to prime plants for preparing for attack by pests and diseases, and one has been used commercially (Bion). Another method of communication involves chemical signalling through the runners, which connect many networks of plants such as strawberries and clovers. If one plant in the network is stressed, then this signal is communicated to all others. Plant communication may have untapped potential for improving plant husbandry and productivity.

C10. How can we use our knowledge of the molecular biology of disease resistance to develop novel approaches to disease control?

Reliable food production cannot be achieved without dealing with the pests that annually devastate harvests. We know that disease resistance in plants depends on their capacity to detect molecules from the pathogen. Plants recognize conserved pathogen molecules, such as fungal chitin or bacterial flagellin, and activate defence. It is clear that not all plants recognize the same spectrum of conserved pathogen molecules, and it is possible to enhance resistance in one species by moving in recognition from another species. Pathogens make "effector" molecules specifically to shut down activation of these defences. Plants can evolve resistance genes that confer recognition of these effectors; pathogens evade this resistance by deleting or altering the recognized effector. Right now, it is lengthy and laborious for a breeder to introduce a new resistance gene into a crop variety. With molecular biology, we should be able to dramatically increase the supply of new resistance genes. This could be done by enhancing the rate of cloning new resistances from wild crop relatives and putting these genes into crops by GM (genetic modification) methods. Also, as resistance mechanisms are better understood, it is conceivable that methods could be developed to engineer an even bigger supply of synthetic resistance genes in laboratories.

C11. What are the mechanisms for systemic acquired resistance to pathogens? Around one quarter of the world's crops are lost to pests and diseases. Improving our knowledge of how plants defend themselves against disease will be central to combating plant infection. When leaves fight off infection, other leaves on the plant receive a signal that "primes" them for more rapid and powerful activation of defence if they subsequently also get infected – defined as systemic acquired resistance (SAR). Some of the molecules involved in SAR have been identified, and we have a good understanding of how these molecules activate defence, but the movement of the signal around the plant is still poorly understood. Furthering our understanding of SAR could help us to strengthen the innate immunity of plants in the future and control disease.

C12. When a plant resists a pathogen, what stops the pathogen growing?

Many phenomena are correlated with activation of defence. Defending plant cells make antimicrobial chemicals, fortify their cell wall, produce a local "bleach" of hydrogen peroxide and, ultimately, self sacrifice and die, resulting in a less congenial environment for microbial growth. However, take away any one of these components and the plant is usually still resistant. We can expect that for different microbes, different components of plant defence are more or less indispensable, and plants have never needed to "fine tune" a unique defence combination for each pathogen. A better understanding of how plants respond to attack will help increase the chances of strengthening plant defences and increasing pathogen resistance.

C13. How do pathogens overcome plant disease resistance, and is it inevitable?

Plants have been in an 'arms race' with the diseases that infect them, for millions of years. The defence mechanisms that plants evoke to protect themselves consist of multiple components some of which are easier than others for microbes to evolve to overcome. Where a single resistance gene confers resistance to a pathogen, it is likely that this gene confers recognition of a single pathogen molecule and usually pathogen variants arise in which this molecule is mutated or lost so that the resulting mutant race can overcome the resistance. However, if a plant resistance gene confers recognition of a molecule that is indispensable to full pathogen function, the resistance gene may be effective for many years, because mutant pathogens that lose the molecule are less fit. Resistance can also be triggered upon recognition of pathogen components that are less mutable and these should also confer more durable resistance. Insight into these issues should help us to improve pathogen control and combat disease.

C14. What are the molecular mechanisms for uptake and transport of nutrients?

Plants require at least 18 chemical nutrients to grow and survive. These include carbon, oxygen and hydrogen, which they obtain from the air and water, plus minerals required in large amounts (the macronutrients nitrogen, phosphorus, and potassium, plus calcium, magnesium, silicon and sulphur,) and micronutrients such as boron, copper, chloride, iron, manganese, molybdenum, sodium, selenium, and zinc. These nutrients exist dissolved in the soil water and are generally taken up through the roots and transported through the plant to sites of growth and metabolism. Plant roots secrete compounds (root exudates) that improve the accessibility of nutrients, either directly, or by encouraging beneficial interactions with microbes whose activity makes the nutrients available in a form that plants can take up. In some cases symbiotic associations are important, as in the fixing of atmospheric nitrogen in legumes by N_2-fixing bacteria in root nodules, and the uptake of nutrients through association of plant roots with soil fungi (mycorrhiza). Plant root hairs also increase the uptake of nutrients, especially those such as phosphorus that do not move easily through wet soil. The entry of dissolved nutrients into root cells is a selective process and can involve specific proteins that recognize the required nutrients and function as passive molecular carriers or active pumps, transporting them across the cell membrane. Once taken up nutrients are translocated throughout the plant; again this can involve specific protein pumps and carriers. Nutrients eventually reach the xylem and phloem, through which they can be rapidly transported around the plant. Improving the efficiency of plant nutrient uptake would improve the efficiency of fertiliser use, reducing waste and environmental damage.

C15. Can we use non-host resistance to deliver more durable resistance in plants?

The selection of plants, particularly those used as crops, for resistance to disease has been a major objective of most plant breeding programmes. Although this has in many cases been very successful, achieving durable resistance to a number of important pathogens, such as *Phytophthora infestans*, which causes potato blight, has proved to be a considerable challenge. Most plants are naturally resistant to the vast majority of potential pathogens; for example, wheat is resistant to *Phytophthora infestans*. An understanding of this phenomenon, known as non-host resistance, will be important in developing long-lasting resistance in plants that we want to protect. Current research is leading to greater knowledge of the mechanisms of this type of resistance, particularly in model systems such as Arabidopsis and wheat powdery mildew, and potential non-host resistance genes have been identified, providing new opportunities for developing plants with durable resistance in the future.

D. Understanding and Utilizing Plant Cells

D1. How do plant cells maintain totipotency and how can we use this knowledge to improve tissue culture and regeneration?

Stem cells, often called meristem cells in plants, retain the ability to regenerate whole new tissues or even complete new individuals, and in plants many types of cells remain capable of forming a new organ or a complete new plant. This ability of a single cell to regenerate into a complete new organism is called totipotency. The phenomenon of totipotency depends on the retention of a complete set of genes by a cell in a state where they can all be reactivated in order to regenerate a complete new organism. Individual cells may require specific environmental conditions in order to regenerate. The production in a laboratory of thousands of new plants from small pieces of tissue or even single cells (tissue culture, or micropropagation), depends on cells being totipotent. Tissue culture is now widely used in plant research, plant genetics and breeding, and is important for agriculture and horticulture. For some important crops, however, it is still very difficult or impossible to carry out tissue culture successfully. With more knowledge it should be possible to overcome this practical problem.

D2. How is growth and division of individual cells co-ordinated to form genetically programmed structures with specific shapes, sizes and compositions?

To successfully produce specialised structures such as grains, flowers, or roots, plant cells need to cooperate so that the changes that they make as they specialise are coordinated. Otherwise, structures would not develop properly, and crucial tissues such as the epidermis and cuticle that protect the surface of the plant, or the xylem and phloem that transport food and water through the plant might be incomplete or become damaged as they tried to grow. By unknown mechanisms the rate of cell expansion, and the amounts and locations of new material laid down by neighbouring cells, must be coordinated so that they can keep pace with each other. Finding out how this is controlled could be useful, for example, to improve plant healing (when plants have to grow new tissue to repair damage), or to produce novel plant structures with desirable properties.

D3. How do different genomes in the plant talk to one another to maintain the appropriate complement of organelles.

A plant cell contains two types of organelles, plastids, whose major function is photosynthesis and mitochondria, whose major function is respiration. Since these organelles evolved from ancient bacterial symbionts they possess their own genomes. The cell must have a surveillance system to ensure that the necessary number and activity of organelles is maintained, but at the moment we know very little about this. Understanding these mechanisms will reveal how stable endosymbiosis has been achieved.

D4. How and why did multicellularity evolve in plants?

One-celled plants (photosynthetic cells) were almost certainly the first truly terrestrial organisms. Today, plants with bodies made up of many cells of many different types provide the structure, resources (e.g., oxygen, food), and complexity that supports the rest of life. The evolution of a multicellular body has probably happened more than once in plants. Cells are natural compartments and many important biological functions need to be separated into separate compartments. For example, nitrogen fixation cannot take place in cells containing oxygen, but photosynthesis produces oxygen. A solution, found in blue-green algae, is to carry out these two functions in separate cell types. Many other specialised functions, such as the programmed lignification and death of xylem cells, which act as transport vessels and structural components that permit plants to grow up away from the ground, have enabled evolution and adaptation in different circumstances producing the complexity of plant life that we see today. Ideas about the principles underlying the evolution of multicellularity are intriguing, but remain to be rigorously tested. Successful research would enlighten our understanding of the history of life on Earth, as well as suggesting possibilities for the future.

D5. How can we improve our understanding of programmed developmental gene regulation from a genome sequence?

In order for specialised plant parts such as leaves, flowers, fruit, or seeds to be produced, specific subsets of genes have to be switched on in the appropriate place and at the appropriate time. We have a basic understanding of how plants achieve this, but there is not a single example where we can describe how the process actually occurs. To do this we need to understand how the DNA sequence interacts with proteins and RNA to modify (e.g. by methylation) and package the DNA (e.g. around histones). We then need to know how the DNA sequence attracts regulatory proteins (e.g. RNA polymerases, transcription factors) to specific parts of the genome at particular times and locations. If we fully understood how this worked it could help us to understand new genome sequences much more quickly as we would be able to predict how the sequence of DNA bases in the genome would translate into gene expression patterns.

D6. How do plants integrate multiple environmental signals and respond?

Plants are exquisitely sensitive to their surrounding environment and modify their development according to environmental signals. Plants are continuously bombarded by a range of environmental signals, such as temperature, light intensity, water availability, nutrient availability, pathogen attack, insect infestation and animal herbivory. The plant must integrate these diverse signals and “decide” how best to respond. However, the range of possible responses is very broad and the plant must balance the range of potential threats and benefits confronting it and make appropriate decisions on resource allocation. Such adaptability is essential for the sedentary lifestyle of plants. The mechanisms that underpin this adaptability involve a complex signalling web that includes plant hormones and acts to modulate cell biochemistry and gene activity to generate the appropriate response. Understanding how plants deal with, and respond to a multitude of environmental signals could help to develop crops better able to cope with climate change.

D7. How do plants store information on past environmental and developmental events?

Plants are able to 'memorise' information and use it to function more effectively. They retain information about their developmental state and their physical environment (e.g. to flower in season or to prepare for oncoming cold in winter), as well as their interactions with other organisms (e.g. to develop systemic acquired resistance to pathogens or to discourage grazing by animals). Plants store information about past events by changing the structure of existing molecules, synthesising new molecules, or producing new cell structures or organs. In some cases aspects of the mechanism, such as epigenetic change, are known but quite poorly understood. In other cases nothing is known about the mechanisms. As plant memory affects numerous processes that are important to humans, we are likely to benefit from an improved understanding of these issues.

D8. To what extent do epigenetic changes affect heritable characteristics of plants?

The fact that the nucleotide sequence of a gene determines the amino-acid sequence of its protein product, and that mutations in the base sequence can lead to altered proteins, are both beyond doubt. We now know that DNA and chromatin modifications other than base changes (such as DNA methylation or local histone modification, and collectively known as epigenetic changes) can affect the phenotype, which leads us to ask which of these may be inherited and for how many succeeding generations? What is their extent, how are they maintained during the lifetime of a plant and transmitted to its progeny? When such changes have been induced by interaction with the environment, this opens up the possibility of the inheritance of acquired characteristics – long dismissed by mainstream genetics, but which may now find its place, albeit in a minor role.

D9. Why are there millions of short RNAs in plants and what do they do?

The existence of small RNAs has been recognised since the 1990s but their function, complexity and significance has only recently been fully appreciated. Plants have millions of small RNAs, far more than in many other types of organism, and the tantalising question is: What do they all do? Apart from long-established roles as ribosome components and small transfer RNAs, there are small RNAs that are involved in defence against foreign DNA (small interfering RNAs), regulating the expression of a plant's own genes (by micro RNAs), removing non-coding regions (introns) from specific mRNAs during their formation (mRNA splicing), and even changing the genetic code of mRNAs after they are copied from genes. Small RNAs are copied accurately from regions of a plant's genome, so each one has a specific sequence that enables it to target a precise DNA or RNA molecule in the cell and carry out a unique function. There are still many unanswered questions about the production and action of small RNAs, particularly in defence and the control of gene expression and plant development, and there may be other roles that are yet to be discovered. Providing the answers to all these questions is likely to provide major new biological insights and will be a major challenge for the foreseeable future.

D10. What is the diversity of plant protein structures?

Proteins are essential for life and plants contain tens of thousands of different proteins, many of which have unknown structures. The three-dimensional structure (shape) of each protein determines what it will interact with and therefore how it will act biologically. It is essential that proteins recognise and interact appropriately with their partner proteins and other molecules in the cell. Their structure determines exactly how they control cellular biochemistry and gene activity and underlies growth, productivity, and composition of all living organisms. Different protein structures do different things, and understanding structure is the key to function - for example, the difference between a protein that makes good bread and one than doesn't is the way that its shape changes when the bread rises; this depends on the protein structure. It is difficult to be sure how many diverse protein structures there are in plants. Presently only 2% of the 40,000 protein structures listed in the NCBI Structure database are from plants. Because plants have many biologically unique features (for example, production of plant cell walls and certain vitamins) many important plant proteins are only distantly related to proteins from other species. Since new protein structures are more likely to be determined for proteins that resemble previously known structures, this delays progress towards the identification of structures for many plant proteins. Much more information is needed in order to know how plant proteins work, and understand the many important functions and valuable reactions that they control.

D11. How do plant cells detect their location in the organism and develop accordingly?

If all plant cells were identical then a plant would be an unstructured mound of cells. The specialised properties of plant parts (stem rigidity, flower shape/ colour/ smell, grain protein content and so on) arise when cells utilise specific subsets of their genes to specialise in ways that suit their location within the plant. Whilst we know some of the general mechanisms involved in some cases, such as transcription factor expression and plant hormone signalling, there is not a single example where the process is fully described or understood. Understanding how this is controlled would reveal how multicellular plants evolved and could be used, for example, to increase plant productivity or generate new types of plant products by optimising the arrangement of cell types for specific tasks and growth conditions.

D12. How do plant cells restrict signalling and response to specific regions of the cell?

Many aspects of plant structure and behaviour depend on cells being able to restrict signalling and responses to specific regions of the cell. For example, the waterproof waxy cuticle that prevents plants from drying out must only form on the outward-facing surfaces of cells on the exterior of the plant. Understanding how localised signalling happens is fundamental to understanding how asymmetry arises, for example, to produce a top surface on a leaf that is different from the surface on the underside of the leaf, or to make the inside of a tissue different from the outside. As disease resistance often involves local responses to pathogens, understanding localised signalling will also help us to understand important aspects of disease susceptibility and resistance. In the long run, we may even be able to successfully tailor plant signalling and responses to generate novel plant structures, such a bespoke plant fibres.

D13. Is there a cell wall integrity surveillance system in plants?

All plant cells are surrounded by a rigid cell wall made up of a range of polysaccharides and proteins. The cell wall is a dynamic cellular compartment that is continuously developed and modified. Plants monitor the integrity of their cell walls in order to receive and respond to information about the environment, particularly attack by fungi and bacteria, but also beneficial interactions such as those with nitrogen-fixing bacteria. Plants can detect small wounds at penetration sites caused by enzymic or physical disruption of their cell walls. They sense oligogalacturonic fragments from their walls produced by the action of pathogen enzymes and also produce chitinase enzymes, which can generate fragments (chitin oligomers) from pathogen cell walls. Sensing of these cell wall fragments activates a range of defence reactions, including: the deposition of additional cell wall material (callose) at sites where penetration is attempted, the production of anti-microbial phenolics and toxins, and the formation of a range of enzymes that can counter the invading pathogen. Part of the surveillance system is located in the cell membrane, and involves not only perception of fragments and pathogen-derived proteins, but also mechano-sensors that detect changes in pressure or stretch and, by signalling, activate response systems in the cells. If we could understand more about these surveillance and signalling systems it could help in breeding plants better able to withstand infections, and might also enable us to extend the range of plant interactions with beneficial microbes, such as those that can fix atmospheric nitrogen.

D14. How are plant cell walls assembled, and how is their strength and composition determined?

Plant cell walls protect plants from the environment including pathogens, and are also important for communication between cells. Cell walls are complex networks of large molecules. The wall is laid down in three stages: a pectin-rich middle lamella, then the primary cell wall, and finally a secondary cell wall. Cell wall construction and modification is a continuous process during the life of a plant and requires the co-ordinated action of hundreds of different enzymes, working both inside and outside the cell. Production of new wall material must take place for plants to grow. Modifications to cell walls can occur at different stages of the life cycle, for example during the growth of tree trunks, the formation of stems, flowers and fruits, and during defence against pathogens. Cell wall structure and composition varies in different species and in different plant parts, and walls can be tough, dense and rigid; flexible; thin and light; or succulent. These properties are determined directly by the precise number, length, chemical composition, and cross linking of each of the different carbohydrate and protein components used to construct the wall. In most cases we only have a general idea of how the construction and assembly of wall components is regulated, and contributes to wall properties. It is essential to improve this understanding in order to more efficiently develop new and better plant products.

D15. Can we usefully implant new synthetic biological modules in plants?

Can we engineer plants to become the chemical or electrical factories of the future? To achieve such a goal will require a step change away from manipulation of single genes and proteins towards a methodology that utilises new pathways and well-characterised complex systems. This type of approach, often termed synthetic biology, applies engineering principles to biology. Individual components (often based on natural examples) are combined together to form modules that carry out specific functions. Successful application of synthetic biology will require significant technical advances, but it has great promise for the future.

D16. To what extent can plant biology become predictive?

If we can successfully predict what a plant will do then we will have the intellectual satisfaction of knowing that we truly understand how the plant works. Much more importantly, however, this depth of knowledge would enable us to conduct large numbers of virtual experiments on computers, so that we could find out much more quickly and economically how best to proceed. For example, progress towards more sustainable agricultural practice would be greatly accelerated if we could reliably predict how plants would respond to new regimens. In some areas of plant science a small degree of prediction is already possible, but how good can our understanding get? What are the limits of predictability and can useful levels of predictive power be acquired within realistic budgets and time frames?

D17. What is the molecular / biochemical basis of heterosis?

The term "heterosis" describes the fact that offspring produced by crossing two genetically different parents often exhibit better performance/characteristics than either of their parents. This phenomenon is known as hybrid vigour. Although several hypotheses exist to explain this in general terms, it is still difficult to predict which pairs of parents will give the best hybrid progeny. A better understanding of heterosis would greatly increase the efficiency of hybrid breeding programmes, and possibly unlock unexploited step-changes in crop productivity.

D18. How do we achieve high frequency targeted homologous recombination in plants?

Plants possess extremely accurate systems to recombine and repair their chromosomes; it would be extremely useful to be able to harness their correction systems to replace stretches of DNA in the chromosome with new or modified sequences. The ability to do this precisely would allow highly-targeted mutations to be made, without the risks and inconveniences of current methods, which can leave unwanted changes elsewhere in the genome, are inefficient, and are not applicable to all species.

D19. What factors control the frequency and distribution of genetic crossovers during meiosis?

When plants reproduce sexually, homologous chromosomes pair and genetic information is exchanged between chromosome pairs via crossover events. This process shuffles the genetic information that is inherited in the subsequent progeny and generates variation for selection by evolution or breeders looking for useful traits. However, the exchange of genetic information does not seem to happen to the same extent in different regions of the chromosomes - some groups of alleles tend to be inherited together in blocks, whilst others are not. Understanding how this is controlled would reveal an important mechanism of evolution and could be used, for example, to breed useful new varieties more quickly and efficiently.

D20. How can we use our knowledge about photosynthesis and its optimization to better harness the energy of the sun?

Plants capture the sun's energy to fix gaseous carbon dioxide, which provides the human population with the foundations of our food and energy needs. Over 85% of the world's energy demands are met by the utilisation of coal, oil and gas, all of which are fossilised plant material and are therefore ultimately generated via energy from the sun. As these fossilised photosynthetic reserves are depleted, human societies will become more dependent on the planet's existing photosynthetic capacity. Photosynthesis uses the greenhouse gas carbon dioxide from the atmosphere so in theory has the potential to provide a sustainable solution for our global energy needs. Is there a better way to harness the sun's energy? For example, could a better understanding of how plants capture light energy, carry out charge separation and store energy be used to design better photovoltaic cells? Alternatively, if we could figure out which is the most efficient photosynthetic mechanism, by comparing light harvesting and energy capture in different photosynthetic organisms, we could then exploit the underlying genes and pathways at an industrial scale.

D21. Can we improve algae to better capture CO_2 and produce higher yields of oil or hydrogen for fuel?

Algae provide a very attractive means of capturing solar energy and converting it to biofuels. They can rapidly be grown in areas that are not used for food or other products, they don't need fresh water, and they can generate oil, biomass and even hydrogen as results of the photosynthetic process. However, there are problems to overcome if we are to fully exploit algae as solar convertors. For example current strains of algae that make compounds that are excellent starting materials for diesel production are slow growing, and yields of hydrogen from algae are too low for economic viability. Exploring the diversity of algae that exist in nature might help overcome these problems. We will also need to develop new engineering methods to harvest and process the large quantities of algae that will be required for production on an industrial scale. Current engineering challenges include the control of pathogens and the development of methods to combine algal CO_2 capture with CO_2 emission at sources such as power plants. Further research is required to release the potential benefits that algae offer as an absorber of carbon dioxide and an energy generator.

D22. How can we use our knowledge of carbon fixation at the biochemical, physiological and ecological levels to address the rising levels of atmospheric carbon dioxide?

Photosynthesis carried out by green plants, algae, and microbes uses light energy from the sun, together with carbon dioxide from the air, plus water and simple nutrients from the environment, to make complex sugars and other organic molecules required for life. This naturally removes carbon dioxide from the atmosphere but has not been sufficient to keep pace with increased CO_2 production by human activity and most people now accept that this is causing climate change. To address this problem, we need to reduce CO_2 production and remove CO_2 from the atmosphere. A better understanding of the molecular mechanism of light capture by plants could improve energy conversion by solar panels and provide energy without concomitant production of CO_2. Photosynthesis could also be used to remove CO_2 from the air, especially if the carbon could be converted to a form that would not be released back into the atmosphere (such as the carbonate structures called coccoliths deposited by single cell algae, or biochar charcoal formed by pyrolysis of biomass). Reducing deforestation and increasing forestry, particularly on non-agricultural land, or increasing the growth of algae in the oceans could also form part of the solution.

D23. What is the function of the phenomenal breadth of secondary metabolites?

Secondary metabolites are chemicals produced by plants, which serve no primary function for example in photosynthesis or reproduction. The diversity of chemicals is vast and many thousands have been identified and the "chemical signature" can be used as a taxonomic trait (e.g. plants in the crucifer family all contain the "mustard smelling/tasting" glucosinolate secondary metabolites). These compounds provide a treasure chest of natural products, which are widely used by man for drugs, fragrances and flavouring agents. The principle function seems to be involved in ecological interactions such as plant defence as many have specific negative impacts on other organisms such as herbivores and plant pathogens. They can also attract pollinators and seed-dispersers enhancing even more their importance in driving ecological interactions and food-webs. Over one in ten pharmaceutical drugs are based on rainforest plants, even though few have had their secondary chemistry fully analysed. Ethnobotany has helped identify the plants used for tribal medicine, and collecting expeditions have generated a library of material for chemical analysis. The treasure chest needs to be unlocked to generate many more novel products of use to society.

D24. How can we use plants as the chemical factories of the future?

Humans have been manipulating the genetics and biochemistry of plants since farming began millennia ago. The use of recombinant DNA technology, especially genetic engineering, now allows us to develop plants that can make a wide range of chemical products. These include novel plastics, vaccines and pharmaceuticals enhanced or manipulated natural products such as accumulations of edible or industrial oils or altered lignin (for paper) or starch (for milling). The possibilities for replacing fossil materials are immense as plants can operate as "mini-factories" offering renewable, biodegradable sources of a range of products including detergents, nylons, lubricants and plastics. Although it is theoretically possible to metabolically engineer any biochemical pathway in plants, altering the biosynthesis of many primary and secondary metabolites remains very difficult, as does convincing society of the safety of engineered plants.

D25. How do we translate our knowledge of plant cell walls to produce food, fuel and fibre more efficiently and sustainably?

Cell wall properties are important to humans. The precise structure and composition of the walls underlies, for example, the properties of cotton fibres, the strengths of different types of wood; the environmental cost of wood pulp processing for the paper industry; the succulence and storage life of ripe fruits, and the crunchiness and cooking quality of fruits and vegetables. Large quantities of waste cell wall materials are produced as a result of production or processing of wood, food and fibre for human use. More effective use of these by-products, for example to produce biofuels, could help to reduce environmental impacts. At present we understand the general principles of cell wall construction and properties but many of the details remain unclear (see the next question). We need to understand much more about the detailed biochemistry of cell wall structure, synthesis and metabolism in order to produce and utilise cell wall materials more effectively. We also need to understand how cells regulate the amount of cell wall they make. This is a great challenge. It will require new scientific approaches (existing approaches are delivering incomplete answers) but may provide the knowledge to improve the production and utilisation of food, fuel and fibre and reduce environmental impacts.

E. Diversity

E1. How much do we know about plant diversity?

If we define plants as organisms that photosynthesise, plant diversity is distributed in several lineages of eukaryotes and in most of Earth's biomes, including the deep seas. Even in those plants we think we know best – terrestrial vascular plants – new species are discovered at the rate of several thousand per year, with little slowing in the rate of description. Most new species are rare and of restricted distribution. The global distribution of diversity is uneven; the tropical regions of the Earth are more diverse in many (but not all) groups of plants and animals. The GSPC has as one of its targets the production of a working list of all (vascular) plant species; this list is envisaged as an expanding process that will continue to be refined as we accumulate knowledge. Species diversity in other plant groups is less well studied. Diversity can be measured in an increasing number of ways, and the integration of new genetic measures with more traditional form and distribution measures will be important for formulating new questions about the evolution of plant diversity.

E2. How can we better exploit a more complete understanding of plant diversity?

A substantial number of plants have potential for human benefit that has yet to be recognised. Current estimates indicate that there are least a quarter of a million flowering plants in the world and the vast majority of these have not been tested for useful properties. The challenge for the future will not only be to find species of value, but also to identify them in a sustainable and responsible manner. Maintaining current habitats across the world will be important to preserve the untapped diversity that exists in the plant kingdom. Plant scientists need to be able to work within a regulatory and ethical framework that supports the effective discovery, commercial and public-benefit exploitation of plants. Natural products provide a greater structural diversity than can be generated by standard chemistry yet it is difficult to exploit this diversity as the complex mixtures of chemicals in plant extracts are often not accessible by high throughput methods. Advances in separation and analytical methods alongside high-speed assays will be needed to by pass this bottle neck. Also, a more complete knowledge of the scale and range of plant diversity across all photosynthetic lineages, not just of those plants thought to be closely related to ones we already use, will help us to understand how plants have solved environmental challenges such as drought or climate change in diverse ways. The resulting knowledge and natural resources will then be available to tackle new challenges as they arise.

E3. Can we increase crop productivity without harming biodiversity?

Increased crop productivity is one way to eliminate human hunger. Increases in productivity can be brought about by improving the crop, through plant breeding, or through agronomic changes such as soil improvement, better use of fertilisers and improved control of pests and diseases. Although this does not necessarily have to be at the expense of biodiversity the evidence suggests that this has been the case in, for example, the UK over the past half century. How these modifications will impact on the survival and diversity of wild plant species, particularly those related to crops, is less well understood, though hotly debated. Greater awareness and understanding of the problems associated with highly productive agriculture will lead to new solutions being found. Modifications of plants also have impacts on the rest of life itself, such as fungi that parasitise plant tissues, the insects and vertebrates that feed on plant parts and the diversity that thrives in the habitats created by plant structures. Research to address this topic will need to incorporate genetics, ecology and plant breeding – fields that rarely intersect. One area being explored currently is to farm intensively within the crop but provide areas for biodiversity to thrive elsewhere on the farm. To work properly this system requires active management of the uncropped, as well as cropped areas.

E4. Can we define objective criteria to determine when and where intensive or extensive farming practices are appropriate?

The terms 'intensive' and 'extensive' as applied to agriculture can, at their extremes be regarded as opposite ends of a management spectrum ranging from very limited exploitation of a virtually wild ecosystem, to farming that involves high inputs (both chemical and cultural). Intensification is generally associated with higher production, but is likely to lead to a reduction in bio-diversity. Extensive farming on the other hand is normally characterized by lower inputs and lower yields.

The current pressure to generate food for a growing population will require increased production with minimum environmental impact. We therefore need to generate data and information that will allow us to make sensible choices about the environmental impact, sustainability and productivity of current and future agricultural systems.

E5. How do plants contribute to ecosystem services?

Ecosystem services are those benefits we human beings derive from nature. They can be loosely divided into supporting (e.g. primary production, soil formation) provisioning (e.g. food, fibre, fuel), regulating (e.g. climate regulation, disease regulation) and cultural (e.g. aesthetic, recreational) services. Plants are largely responsible for primary production and therefore are critical for maintaining human well-being, but they also contribute in many other ways. The Earth receives virtually no external inputs apart from sunlight, and biological and geochemical recycling of matter are essential regenerative processes for life to be sustained. Plants drive much of the recycling of carbon, nitrogen, water, oxygen, and much more. They are the source of virtually all the oxygen in the atmosphere, and they are also responsible for at least half of carbon cycling (hundreds of billions of metric tons per year). The efficiency with which plants take up major nutrients, such as nitrogen and phosphorus, has major impacts on agricultural production, but the application of excess fertilisers causes eutrophication which devastates water ecosystems. Plants are already recognized as important for sustainable development (e.g. plants for clean water) but there are many other ways that plants might contribute. A combined approach of understanding both the services provided by ecosystems and how plants contribute to the functioning of such ecosystems will require interdisciplinary collaboration between plant scientists, biogeochemists, and ecologists.

E6. How can we ensure the long-term availability of genetic diversity within socio-economically valuable gene pools?

The Global Strategy for Plant Conservation (http://www.cbd.int/gspc/about.shtml) is a sixteen point plan for the conservation of plant diversity and function that has been endorsed by the UN Convention on Biological Diversity (http://www.cbd.int/), and lays out a path of action for the plant science community. One of the GSPC targets is to see "70% of the genetic diversity of crops and other major socio-economically valuable plant species conserved and associated indigenous and local knowledge maintained". Major crop diversity is currently maintained in germplasm banks worldwide, but the diversity of the many other plants used by people is less secure, as is the wide range of indigenously maintained crop diversity. This must be addressed as the germplasm could play critical roles in future improvement and adaptation in the face of changing human populations and climates.

E7. How do specific genetic differences result in the diverse phenotypes of different plant species?- i.e. why is an oak tree an oak tree and a wheat plant a wheat plant?

Current research suggests that the gene content of different plant species is surprisingly similar, and that many of the differences between individuals and species originate from the alleles (different versions) of each gene they carry, including regulatory alleles that affect the timing or extent of expression of other genes. These genetic differences produce the range of species that we see, from annuals (such as Arabidopsis), which grow, reproduce, senescence and die in a few weeks or months, to trees (such as oak, *Quercus* spp.) that over-winter, grow and produce seeds over hundreds of years. To understand this at the molecular level, it is necessary to unravel interactions between hundreds or thousands of different proteins, produced in different amounts, at different times. There are many possible combinations and interactions and to fully understand species differences, we need to compare large numbers of genome sequences, map global transcript levels (presence and abundance), and differences in mRNA translation. This can now be done more quickly and cheaply than ever before. Advances in computer-based analysis and modelling of the complex datasets generated are essential to understand and interpret this information to bring explanations of differences between species within reach.

E8. Which genomes should we sequence and how can we best extract meaning from the sequences?

The development of massively-parallel sequencing methods has made it possible to sequence the genomes of a much wider range of species. Platforms such as Genome Sequencer FLX from 454 Life Sciences/Roche, Illumina Genome Analyzer, and Applied Biosystems SOLiD are providing scientists with a scale and precision of information that was unthinkable 5 years ago and at a price that many labs can afford. For example, the wheat (*Triticum* spp.) genome is being sequenced. To maximise progress steps must be taken to enable comparative analysis by providing reference sequences from a range of species spanning the range from algae to trees. Issues of data analysis and storage remain to be answered. To derive the most benefit from the mountain of sequences that are generated by these new technologies, new methods and tools will be required to translate the highly complex and essentially unsorted information efficiently and effectively into an understanding of how the organism works and interacts with its biotic and abiotic environments.

E9. What is the significance of variation in genome size?

There is an extraordinary variation in genome size amongst plants ranging from 10Mbp in the alga *Ostreococcus tauri* to 125,000Mbp in the tetraploid angiosperm *Fritillaria assyriaca* (http://data.kew.org/cvalues/psgm/index.html). Even within the same genus, genome size can vary more than 20-fold. Although we know that a large number of plant genomes contain significant amounts of duplication, the range of genome sizes is far greater than might be expected. Speciation, hybridisation, and polyploidisation all give rise to changes in genome composition (especially in repetitive elements) by mechanisms that include transposition and recombination, but are poorly understood. Phylogenetic analysis shows that small genome lineages are often embedded within larger-genome clades, suggesting that mechanisms exist that can reduce genome size. At the moment we have no clear idea of the consequences, evolutionary or otherwise, of these enormous changes but the ease and relative low cost of whole-genome sequencing is likely to enlighten our understanding.

E10. What is the molecular and cellular basis of plants' longevity and can plant life spans be manipulated?

The life span of plants can vary from a few weeks (e.g. Arabidopsis, *Arabidopsis thaliana*,)) to several millennia (e.g. bristlecone pine, *Pinus longaeva*). However, there is always a high rate of individual cell death throughout the plant's life. Why does such variation exist? Individual organs, such as leaves, can have life spans, which significantly differ from that of the whole organism. The longevity of leaves has been most researched within the context of what is termed the senescence syndrome (particularly noticeable in autumnal deciduous trees). This syndrome is characterized by distinct cellular and molecular changes that mobilise the nutrients and recycle them from the leaves to the rest of the plant. It has also been demonstrated that changes in levels and/or sensitivity to hormones such as ethylene and cytokinin can affect senescence, and provide an opportunity for manipulating longevity. Thus, whilst we can already use genetic tools to manipulate the longevity of leaves, and possibly whole plants, we still know relatively little about the molecular basis of aging in plants. The ability to adjust the life spans of plants could provide numerous opportunities. For example, it may be beneficial to prolong the life of plants of recreational or amenity use such as floral displays or to increase the useful life of agricultural plants which take time to reach maturity for harvesting. However, the release of plants with a manipulated longevity may raise a wide-range of environmental and ethical issues.

E11. Why is the range of lifespans in the plant kingdom so much greater than in animals?

Most plant and animal species have a range of lifespans varying from weeks through to decades, but the upper range of plant lifespans far exceeds those of animals. The bristlecone pine can survive more than 4000 years, whereas the longest lived vertebrate animals, whales, can barely make 200. Longevity is modulated by the processes of ageing and senescence, and recent ideas suggest that plants and animals show important differences in these processes. A number of "classical" theories (e.g. free radical theory, telomere shortening, stem cells and immortality) offer some explanation as to why plants can live so long, but there are exceptions and outliers to all these theories. What is certain is that phenotypic plasticity can affect the longevity of both plants and animals. Importantly organisms which are immobile (or passively mobile) such as all plants and modular animals (e.g sessile benthic invertebrates) are better equipped with plasticity mechanisms which confer greater longevity than unitary animals which tend to be mobile. Thus whilst individual modular elements of a modular animal or a plant may senesce, the colony/plant can persist. There is considerable interest in ageing research, especially in medicine, and thus improving our mechanistic understanding of ageing from a diverse range of life-spans could underpin new theories and subsequent developments.

E12. What is a plant species?

Species are thought to represent evolutionarily significant units, and are used widely to discuss diversity by both biologists and others. The idea that a species is defined by inability to interbreed (the Biological Species Concept) was widely accepted in the zoological community in the last century. Botanists, however, did not feel comfortable with this very restrictive definition of a species. Hybridisation is widespread in plants, both in terms of genome combination (polyploidy) and at the diploid level, but in general does not erase variation completely. People working with plants therefore tended to define species using practical, observable criteria such as morphology or distribution. It is clear that variation is not uniformly distributed and that observable units are recognisable, but as our ability to investigate variation at ever finer scales becomes easier, criteria for recognition of those units we wish to use as species can become more blurred. The balance between gene exchange and isolation in natural populations drives differentiation, and as it becomes clear that absolute boundaries are not always present, how we combine data from a wide variety of sources to name units for use outside biology will need careful thought.

E13. Why are some clades of plants more species rich than others?

Diversity is not uniformly distributed among lineages of plants. Some lineages, such as that containing the flowering plant Amborella (*Amborella trichopoda*), consist of single species, while others, such as the orchids (*Orchidaceae*), have thousands of species. Genetic diversity too is uneven, with some species exhibiting wide variation in form and gene sequence, often coupled with wide geographic distribution. Other species, however, are more genetically and morphologically uniform and are very narrowly distributed. These patterns are almost certainly the result of a balance between the generation of diversity (speciation and other processes) and extinction, due to both historical and environmental forces. This balance can be difficult to determine – it is tempting, for example, to assume that very diverse lineages are very old and that diversity is thus cumulative. On the other hand, it could be assumed that diverse lineages are the result of rapid and recent diversification, and that older lineages are the less diverse ones. Both of these assumptions have been used to explain plant diversity. Our ability to date lineages using molecular sequence data, and to investigate fine details of genomic structure will allow us to investigate the balance between extinction and diversification more finely, and to determine if general rules apply across the range of plants.

E14. What is the answer to Darwin's "abominable mystery" of the rapid rise and diversification of angiosperms?

There is some debate as to exactly what Darwin meant by "abominable mystery", but it is clear that he was extremely puzzled by the apparent rapid rise and diversification of the angiosperms. They went from being absent in the fossil record about 130 mya to be dominant and highly diverse in a very short time, perhaps as little as a few tens of millions of years. Some previous authors had suggested that flowering plants evolved over a much longer period of time but diversified in places that were not good for fossils to form, such as in mountains, but new evidence from comparative molecular phylogenetics overwhelmingly supports a rapid and relatively recent diversification. If we could understand how this occurred it would provide important insights into how angiosperm genomes changed and the evolutionary benefits of such re-organizations.

E15. How has polyploidy contributed to the evolutionary success of flowering plants?

Polyploidy is the result of whole-genome duplications, most often associated with hybridization, such that the resultant plants have multiple sets of chromosomes compared to their parents. Polyploids can themselves be combinations of other polyploid lineages. Polyploidization most often occurs as a result of failure to undergo meiosis during embryo or sperm development, which produces diploid gametes. Fusion of a diploid sperm with a diploid egg results in a tetraploid. When these come from different original species the result is an allotetraploid. Autopolyploidy, or simple chromosome doubling, also occurs, but allopolyploidy confers more benefits, resulting in a nucleus with much greater gene diversity than the parents or an autopolyploid. In the short term, polyploidy has few advantages, and recent polyploid species have genetic (e. g., how to manage meiosis) and ecological (e. g., competition with their likely to be better adapted parental species for ecological space) challenges to overcome. Longer term, there do seem to be benefits from the widespread gene duplications that are a result of polyploidy, which seem to allow much greater control over levels and quality of expression. There is good evidence from several studies that one episode of polyploidy is coincident with the explosion of lineages that took place about 140 million years ago; could it be that polyploidy fuelled angiosperm diversification?

E16. What are the closest fossil relatives of the flowering plants?

Flowering plants are the dominant life forms of our planet, but we still know little about their evolutionary origins, particularly how flowers came into existence and what the counterpart structures are in gymnosperms and other land plants. There are many groups of fossil plants already known to us, but how these are related to the flowering plants is highly speculative so there is little point in debating if they could serve as models for how flowers evolved. Study of the fossil record is therefore important, as is developing a clearer understanding of the genetic controls of flowers and how these genes function in extant gymnosperms. Solving this riddle will improve our ability to use angiosperms appropriately because it will give us important insights into how they function and adapt.

E17. How do we best conserve phylogenetic diversity in order to maintain evolutionary potential?

One of the main aims of conservation is the preservation of the diversity of life on Earth. Conservation has been focused on species richness for a long time, but it is clear that species richness alone is not the best measure of diversity. Lineages arise, diversify and go extinct over geological time and the diverse world of plants we have today is the result of these processes. Conservation of a resilient world able to recover from environmental challenges, such as those that have happened in the past, may rely on the conservation not just of numbers of species, but of as many of the branches of the tree of life as possible in order to maintain potential for evolutionary change. In order to achieve this new and challenging goal we need not only to have good, robust hypotheses about the phylogeny of all branches of plant life and a good understanding of their geographical distribution, but also the societal impetus to work together to conserve the future of plants for our own futures.