2009 Frank Arden Memorial Award

Nuffield Farming Scholarships Trust

Science and Technology

For

Farming and Food

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Thanks.

I am indebted to the Nuffield Farming Scholarships Trust, the Frank Arden Memorial Trust and Natural England for their support and for affording me the opportunity to carry out this study. My thanks also go to the great number of scientists and commentators I met and spoke with along the way, collectively they have transformed my view of science, technology and the world at large. My sincere thanks to John Stones for his support and guidance throughout. To Carolyn, my wife, for whom this period delivered challenges and changes the like of which neither of us could have imagined, gratitude beyond words.

Abstract.

The case for increased and sustainable food production is being made almost daily. The impacts of increasing population, dwindling natural resources and climate change are converging to present an unprecedented set of challenges.

This review sets out to examine how science and technology can contribute to finding solutions for the UK agriculture and food sector, to create a functional, competitive and relevant industry.

It will reveal how new technologies will influence and shape the way established science develops. For example, it will look at nanotechnology and how work in that sphere might influence the way energy is sourced, stored and ultimately used; how advances in plant science and genetics will combine with new engineering and artificial intelligence to transform the way crops are grown and how knowledge of life in the soil will change the way plant scientists drive their research priorities.

Finally, it will support the case for the restoration and re-invigoration of the partnership between the practice and science of agriculture.

Introduction.

Overview.

This study began as a global review of agricultural science; a huge area and one where the notion of a detailed study of all branches of science and technology would be impractical.

By necessity it became a superficial investigation across a spread of disciplines, taking a look at the current state of knowledge, examining new work and ideas and then outlining the potential in a UK context with special reference to the opportunities for UK farmers.

The areas of study highlighted are representative of the wide field of science and were chosen to illustrate how progress will eventually be influenced by the way in which strands of work develop in parallel if not in synchronous. Eventually, problems overcome in one area will allow another area to come forward.

Motivators of Change.

When planning our activities at an individual business level, we should not accept the need to change or to adopt new techniques as a given. In any planning process it is sound procedure to review where the business is, what is threatening it, what the opportunities might be and how the strengths of the business can be harnessed to capture them.

The concept of the 'perfect storm', a coincidence of global events as described by Professor John Beddington[1], Chief Scientific Advisor to the UK Government, provides a range of motives for change. This describes a number of factors of universal significance which international and national policy makers will ignore at their peril.

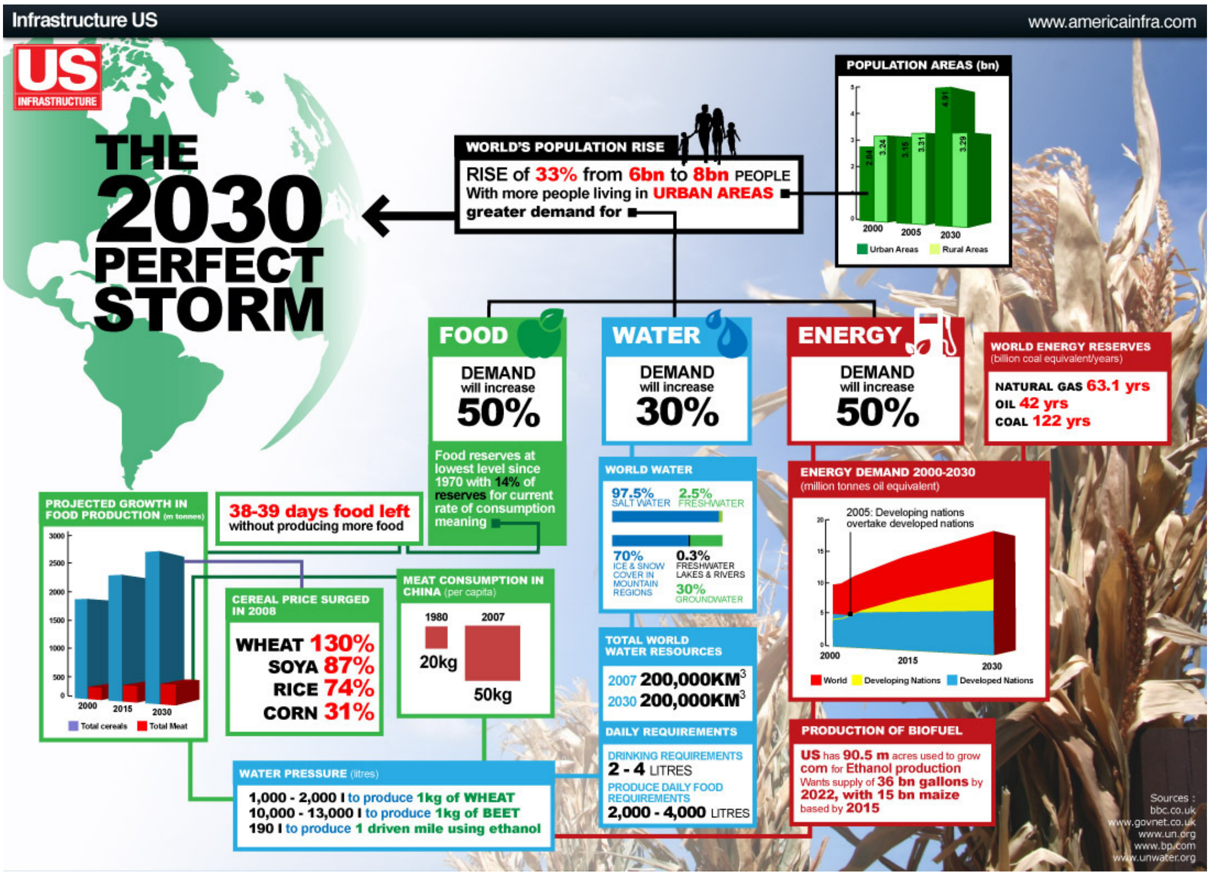

Fig. 1. The '2030 Perfect Storm' .

Climate change: we now know that the earth's atmosphere is warming and that the average surface temperature will rise by between 1^{o} and 2^{o} Celsius over the next 20 years[2]. The UK is likely to experience warmer, drier summers and milder, wetter winters. This will impact on the choice of crops grown, the way they are watered, the peak growing season and the length of growing seasons. These changes in weather will mean that the characteristics of the crops we grow today will not necessarily suit the conditions of the future.

Fresh water: we know that the world's fresh water supply is under pressure and is regarded as an increasingly scarce and precious resource. The concept of 'embedded water' is growing in profile. This term describes the amount of water needed in the production of goods or provision of services and is used to suggest a level of dependence on water.

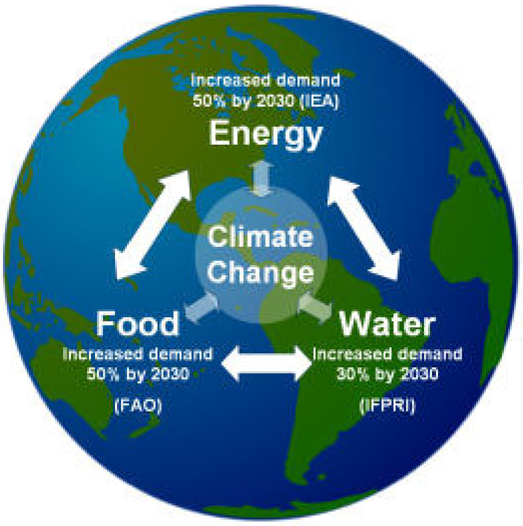

Fig. 2. Graphic to illustrate the effects of population growth on the demand for energy, water and food exacerbated by th effects of climate change.

Environmental impact: growing populations have led to increased urbanisation with now over 50% of global population living in cities, thereby eroding the area of land available for agriculture. Western agriculture relies heavily on mineral fertilisers and agrochemicals which require energy to produce and which can cause diffuse pollution problems in the wider environment if they escape from the production cycle.

Energy: agriculture is a significant user of energy, most of which is currently derived from fossil fuels.

Population growth and increasing affluence: Not only is the population growing, but so is affluence. Richer people tend to eat more meat which in itself places greater pressure on global resources.

The elements listed above have serious implications for all of us, and dealing with them is a collective matter. However, we cannot expect individual businesses to take responsibility for factors over which they have no individual control, especially if in so doing they put themselves in a commercially weaker position. In order to change individual business behaviour to tackle these kinds of issues, we need influence from outside the business. This can come in the form of regulatory change, a change in the law, or it might come from customer pressure, for example a supplier code of practice or protocol.

At an individual business level, the motivation for change is likely to be more visible, shorter term and capable of having an immediate impact on the running or performance of the business. Innovations which give a competitive edge or a marketing gain can be seen in this way. Cost saving developments will improve margins and give the business greater security.

Summary.

In 30 years time agriculture will look very different from today. The pressures described above will shape agricultural and environmental policies. The technologies I am about to describe will shape our ability to respond.

In my studies I found a range of developing technologies, any one of which was capable of delivering an opportunity for change at an industry level. Most of the ‘building blocks’ are in place now, they need to be developed and integrated at all levels through the science and innovation chain.

Areas of Study.

Nanotechnology – the science of the small, not a technology in itself but a collective term to encompass any technology working at the 'nano' level.

Biosystems Engineering – facilitating precision in production and processes.

The Soil – how much do we really understand and how will greater understanding help in developing sustainability?

Plant Life – manipulating genetics to achieve more from less.

Water – making better use of it in biological systems.

Pigs – looking at a livestock sector with a sound record of innovation.

Nanotechnology.

Introduction.

Nanotechnology is not a technology in itself but is a collective term for a set of technologies, techniques and processes describing materials science and applications at the nanometer scale. A nanometer is one billionth of a meter or 10^{-9} and it is generally recognised that nanotechnology operates in the range of 0.1nm to 100nm.

To put that into perspective:

- 1 nanometer — 1 billionth meter (10^{-9})
- pinhead — 1,000,000nm
- human hair — 80,000nm
- red blood cell — 7,000nm
- virus — 100nm
- water molecule — 0.3nm

It is not a new science having been first described over 50 years ago, but it is only in relatively recent times that scientists and process engineers have developed the ability to work at this scale and develop products at a commercial level.

The behavioural properties of materials formulated at the nano scale changes from those observed at the micro or macro scale. This can be seen in, for example, chemical reactivity, physical strength, electrical conductance, magnetism and optical effects. The changes are largely attributable to the much greater surface area to volume ratio at the nano level which in turn allows much more intimate contact with other materials, substrates and reagents and results in a tendency to display heightened properties at the nano scale[3].

Nanotechnology today.

Nanotechnology is already commercially established. Two examples are illustrated in the case studies below, but many others exist, including some agricultural crop protection product formulations.

Case study – Sunscreens: These are the products applied to the skin before exposure to bright sunlight. Commonly used active ingredients are titanium dioxide and zinc oxide, both of which have the property of filtering UV light, thus preventing skin damage from excessive exposure to this potentially harmful radiation. When formulated at the micro scale, these actives are opaque to visible light, whereas at the nano scale they become transparent to visible light but retain their UV filtering property[4]. Thus, in the days of micro formulations it was always easy to see who was wearing sunscreen, the opaque nature giving a white colour to the treated skin. Now with nanotechnology, sunscreen becomes transparent when applied and spread over the skin.

Case study - Self-cleaning glass. This exploits the photo-catalytic and hydrophyllic properties of titanium dioxide when applied at the nano scale as thin film coating to glass. The action of UV light on the coating initiates a process in which organic material is oxidised, thus loosening the material from the glass. The hydrophyllic characteristic means that any water droplets landing on the glass have no surface tension and so will spread evenly over the surface. As long as the glass has a gradient, then the water will spread and run off, carrying any organic debris with it. The coating need only be 25nm thick, the same ratio of thickness as that of a penny piece to the height of the Canary Wharf tower[5].

Nanotechnology tomorrow.

- Hydrogen production – scientists at the University of East Anglia[6] have developed a method of using sunlight to split water into hydrogen and oxygen using nano scale crystals and electrocatalysts. The process uses relatively abundant materials and a light energy conversion efficiency of 60% is within reach. This has major implications for hydrogen powered technologies which so far have been hampered by the cost, both commercial and environmental, of producing hydrogen. Low cost hydrogen is now a realistic goal, both in terms of commercial cost and environmental impact.
- Filament technology or 'nanotubes' – latticed filaments which can be teased into fibres and then woven into sheets. Most commonly fashioned from carbon, this technology has the potential to revolutionise the construction sector. Carbon nanotube technology can produce materials with a strength 100 times that of steel but with only 12% of the density, very light and very strong. This has obvious implications wherever it might be applied.

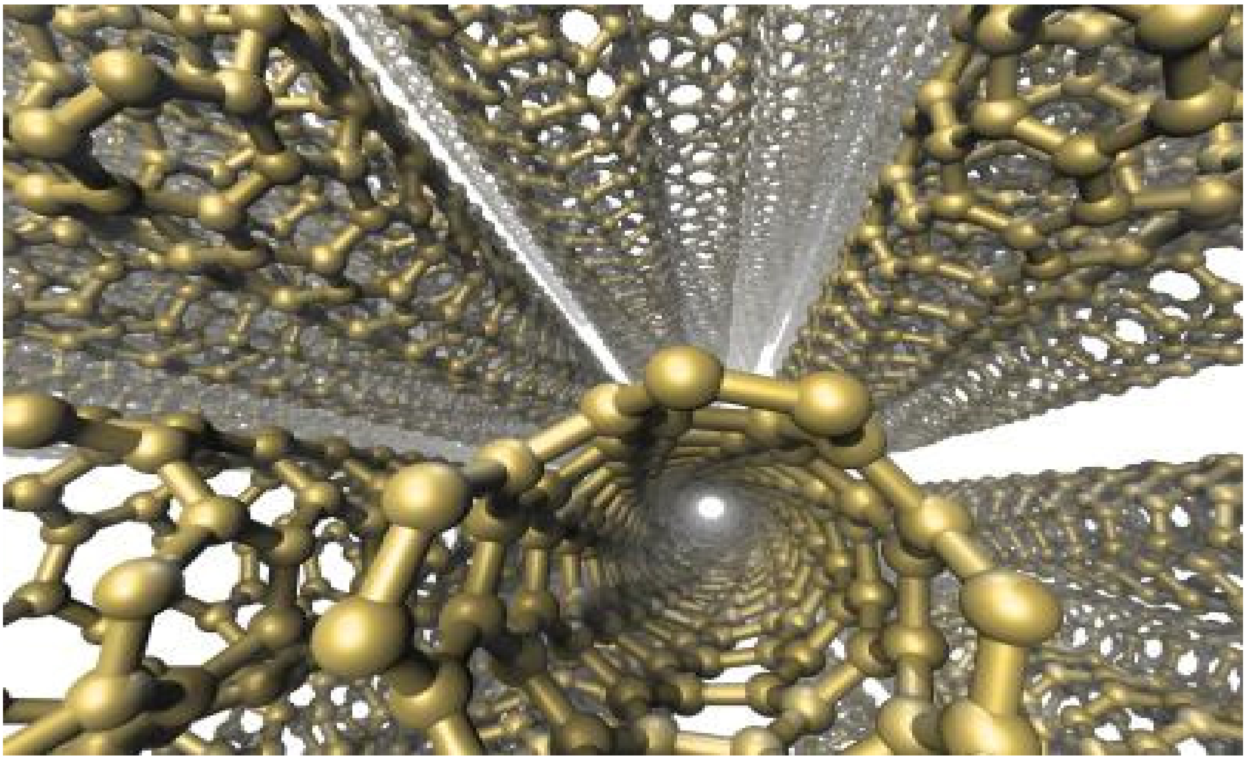

Fig.3. Carbon nanotube

Case Study - Solar energy and Photovoltaics: we have had silicon based solar panels for many years, but working at the nano scale the efficiency of turning sunlight into electrical energy has been transformed from around 20% to 60%. New technology being commercially developed by a joint venture in Wales should be available in 2011. This 'third generation' technology which could be used on flexible surfaces and work in cloudy conditions, uses a manufacturing process cheaper and less environmentally damaging than older systems. Existing 'wafer' technology can deliver 140 watts of electrical energy per m^2 of panel, so the potential for lower cost, higher output nanotechnology-based is very strong. Most farmsteads have buildings with roof areas highly suitable for solar electricity generation, and the relative low weight of nanotech photovoltaic systems means that structural strengthening will be unnecessary in many cases. Farm generated solar electrical energy could make a very significant contribution to reducing fossil-fuel based energy demands, and at sustainable cost.

- Encapsulation – allows a 'controlled release' approach whereby an active ingredient is encapsulated by another molecule which releases the active when exposed to a particular stimulus. This concept is being developed in a wide variety of areas, so called 'smart delivery' systems where for example, fertilisers and nutrients can be 'programmed' to become available over time. Pesticides formulated to release under specific circumstances of temperature, humidity, pH, light, radiation and other environmental stimulants. It is already being used in some pesticide and fertiliser formulations.
- Sensing – small molecule structures inserted in growing crops to give early warning of disease or nutritional imbalances. Similar technology has uses in food packaging, for example wrappers which are impregnated with particles which change colour in the presence of salmonella.

The nanotechnology arena is huge and varied and only the tip of the iceberg has been considered here[8]. There is however a note of caution. We do not know for certain the fate of nanoparticles in the environment and there are those who believe the regulatory processes are not sufficiently robust to give adequate public protection[9]. The scale of these particles is such that they can pass through the gut wall unimpeded, even through cell walls. Nanofilaments can adsorb toxic materials, indeed they are being developed for those kinds of filtering / purification processes. What happens to the toxin-loaded filaments?

Another aspect of nanotechnology is that outside the scientific community it is rarely directly referred to. How many commercially available products have ‘nanotechnology inside’ proudly written on the packaging or even in the small print? There is the potential for a public backlash if the regulatory controls prove wanting. The industry should take care to ensure ‘nanotech’ does not become the PR disaster that GM became.

This technology has enormous potential to enhance and influence other technologies. In energy production from sunlight, there is the potential to regard hydrogen more seriously as environmentally acceptable and for solar electricity to make a much greater contribution. With very light and strong materials a completely different approach can be taken to how machinery is constructed and used. Crop sensing and ‘smart delivery’ technology can be dovetailed with autonomous machines monitoring crops at an individual plant level.

Some of these relationships will be referred to again in this report.

Biosystems Engineering.

Introduction.

The area of science once known as ‘agricultural engineering’ or ‘farm mechanisation’ is now more appropriately styled ‘biosystems engineering’. This reflects the wider spread of disciplines it now encompasses and acknowledges the much stronger linkage to the biological sciences.

This section will consider how this technology is currently used to mechanise, automate and otherwise make more precise the various activities involved in crop and animal production; and then how that knowledge can take us forward and in which direction.

The main areas of work are guidance and data transfer, vision systems, sensing, machine intelligence and robotics.

- Guidance and data transfer – well established commercially and forming the basis of current developments.
- Vision systems – the use of cameras to gather information to inform other systems becoming commonplace.
- Sensing – referring to any method by which data is gathered, and beginning to include elements of nanotechnology referred to earlier with in-crop sensors being used to signal changes in individual plants to which a machine or system can respond.
- Machine intelligence – the process by which information gained is translated into the need to carry out an action, and the execution of the action.
- Robotics – machines capable of carrying out often complex mechanical activities, widespread in factory type installations, used in agriculture for milking cows and stacking pallets.

Current state of these technologies.

These technologies are well established in the commercial world of agriculture. There are guidance systems which allow accurate pass-to-pass travel within a field, routines can be programmed to turn machines round at the end of a field or shut off sprayer booms or vary rates of applications of seeds, fertilisers and sprays. Information systems exist which can tell what a machine is doing and where or can collect information from the soil, a crop, the atmosphere or an animal and transmit that to another place for analysis, action or storage. There are weeding machines using vision systems to identify crops from weeds and act accordingly. There are robots which can milk cows

Expanding the influence of the technology.

There is a natural progression to these technologies which will lead to greater penetration and uptake of their use. However, there exists a major weakness in global positioning and mobile telephone technologies which until resolved, will limit potential. At present, accurate global positioning is too expensive and not sufficiently reliable. This also applies to mobile telephone technology. For real progress to be made, it is vital that machines know where they are, precisely and constantly; and that information can be freely, rapidly and reliably transferred from machine to machine, wherever they are in relation to each other.

To illustrate, high accuracy machine guidance systems for agriculture are based on global positioning satellite systems coupled with a local correction signal. This typically gives +/- 2cm pass-to-pass accuracy. Common problems experienced by current users of these systems include ground feature shading of radio waves, loss of satellite signal and geographical range limitations. The implicit constraints are clear. Potential users whose land includes areas prone to signal shading will not take up the technology, loss of satellite signal renders whole systems inoperable until reinstated. This might be tolerable in some cases but for most it will not. Users operating over a wide geographical area will face high costs in providing signal cover.

Case study – Community RTK Networks. Uptake of guidance technology has been rapid in the grain states of the Mid-West USA. The development of min-till and now strip-till techniques coupled with precision placement of seeds and fertilisers has stimulated the need for 'sub-inch' repeatable accuracy. Minnesota, Iowa and Wisconsin are three states where RTK-GPS with CORS referencing is available on a state-wide network, giving reliable access to signals over a wide area at affordable cost.

There are similar difficulties with communication systems for moving information and commands from the point of collection to the point of application. These may be very close together or very far apart and rely on two technologies. The first deals with communications between tractor and attached machine, so called CANBUS protocols. These are developing but are some way from providing the sophisticated platform needed. The other is mobile telephone technology, needed to transfer data and commands wirelessly. Coverage in the UK remains patchy in rural areas.

The large scale arable agriculture which now typifies UK broad acre farming relies on big machines covering a lot of ground in a short time with little labour input. The guidance and control technologies described are capable of taking this approach to a higher level, especially using accurate positioning to allow controlled traffic farming, a system by which soil compaction is minimised by matching machine size to allow tractor wheels to drive over exactly the same place each time a pass is made. It is claimed this can reduce the tracked area of a field over the course of growing a cereal crop from 127% to 33% with a range of benefits including crop yield increases, lower soil compaction, reduced power requirement for cultivations and reduced fuel usage[10].

To this can be coupled communications technology (telematics) allowing, for example, improved sprayer efficiency by automatic boom section control and variable rate applications of inputs. It can also allow access to more sophisticated functions, for example telematic systems which already exist to monitor some tractors and harvesters[11] remotely whilst at work and to analyse performance and efficiency.

The obvious next step is to extend these systems to allow new levels of control. For example, with knowledge of field shape, size and yield, machine intelligence could calculate the most efficient way of harvesting the field, minimising unnecessary turning and waiting. It could also link to the unloading/carting fleet to optimise whole fleet movements. This is especially relevant where multi-unit fleets are employed, for example road vehicles collecting grain from a number of harvesting sites.

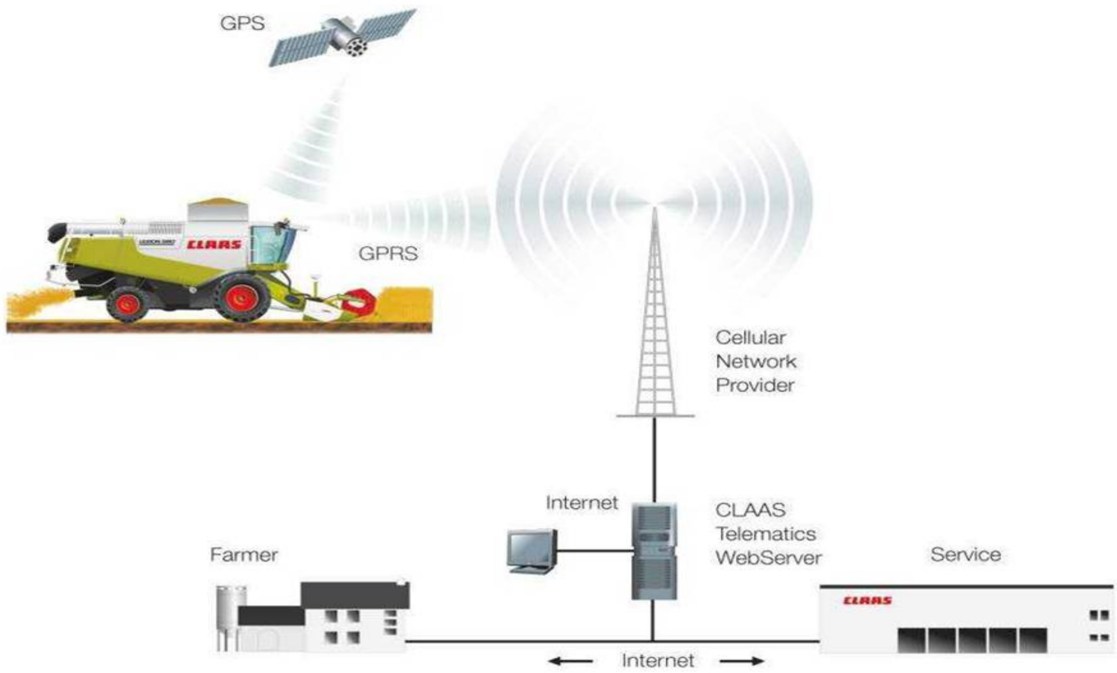

Fig 4 Representation of remote communication.

Towards Autonomic Systems.

Another area is part-time remote control. This is where one machine temporarily takes control of another one. Unloading grain from a combine to a tractor and trailer running alongside is an obvious example, and availability of this technology is imminent[12]. Modern harvesters run at high speed and the unloading operation is highly dependent upon the skill and judgement of the tractor driver and the confidence of the two drivers working in concert. It is not unusual to see combines slow down during unloading, or for grain to be spilled or trailers not be fully laden due to the difficulties which poor visibility, dust and darkness can bring. Automating this procedure would allow less skilled people to be included in harvest teams and simultaneously increase the efficiency of the operation.

Development engineers at John Deere's Intelligent Vehicle Systems facility at Urbandale, Des Moines, Iowa are close to delivering systems which can allow one machine to take temporary control over another but the technical and territorial problems are considerable. For example, which machine takes control? What sort of technology should be used, vision systems or GPS? Can the data be transferred quickly enough? Do local protocols insist on data encryption and will this slow the process down too much? How easily can the system cope with machines from different manufacturers?

Concepts like temporary remote control are most likely to appear first in areas where the market is largest, but with time they will be adapted to many other situations.

As far as total system efficiency is concerned, it is likely that big machines are approaching a theoretical upper limit[13]. It is also a paradox that much of the energy used in arable crop production is expended in undoing the damage done to soils by the very same machines in the previous year.

Thus, whilst it can be seen that guidance and sensing technology can lead to efficiency gains in the medium term, the large size of machines and the need to make provision for an operator on them is placing limits on what can be done, especially when full machine autonomy is considered.

The driverless tractor has been a technical possibility for a long time. A major obstacle to realising it has been the safety issue. This is even more the case now that machines are so much bigger. If new levels of efficiency are to be targeted, and soil and environment considerations given a higher priority, then a more radical approach is required.

Converging technologies.

The mechanisation and automation of western agriculture has developed along a large scale or ‘macro’ structure. This has been largely driven by the perceived need to reduce labour units involved and the development of monoculture cropping. There is a pipeline of development which will continue this trend.

There has also been a need to design machines with space for an operator. Removing the need for an operator removes huge constraints in machine design, function and potential work rate.

There is now a rapidly emerging set of technologies based on a micro scale approach which has the potential to transform crop production techniques.

This is a complete reversal of thinking, moving from the macro to the micro and has exciting possibilities for UK agriculture.

Fig .5 ‘Bonirob’ autonomous crop plot inspection and monitoring vehicle.

The machine pictured in figure 5 is the ‘Bonirob’ autonomous crop plot inspection and monitoring machine. Developed by Professor Arno Ruckelhausen at the University of Applied Sciences, Osnabruck in Germany it is part of an ongoing development effort across Europe to bring forward biosystems engineering to work on crops at the individual plant level.

The Bonirob is designed to negotiate small scale trial plots, fitted with sensing equipment to carry out various monitoring tasks, for example, measure plant height, colour, take a leaf sample. It is now only a matter of development to take this concept on to machines of relevance to commercial farming situations.

Machine intelligence is being developed which will permit greater autonomy of operation. Fully autonomous machines will need to be ‘aware’ of their surroundings and be able to cope with the unexpected. They will need to know in what weather conditions they can operate, whether they have all they need to carry out their tasks, where to go to replenish if they are running low, what to do if they meet an obstacle. They will also need to recognise a system failure and know what to do in response.

All of these systems will need to be in place and fully reliable before the risk assessment will permit truly autonomous operation. Once that fundamental obstacle has been overcome and autonomous operation is accepted with small machine, then the opportunity arises to develop the concept with larger and more sophisticated versions.

Fully autonomous micro scale machines offer a range of possible benefits over manned or unmanned macro scale technology. For example:

- reduced labour cost, robots can work alone
- expanded working time, robots can work continuously
- greater accuracy, consistency and reliability, robots don't tire and are not governed by the working time directive
- more frugal with inputs, working on an individual plant level
- less damaging to the soil, lighter 'footprint'
- less sensitive to field size
- can manage crops on an individual plant basis
- facilitate heterogeneous crop culture
- soils and crops managed more sympathetically.

It is now within rational thinking to believe that small, autonomous vehicles will be at work on UK farms in the relatively near future, allowing a radical rethink of crop production as we know it.

It is already the case that 'min-till' and 'strip tillage' platforms are being developed in the UK, based on improved crop performance through reducing soil disturbance. This can be taken a stage further with micro robot technology, using them to disturb only that area of soil needed to take the seed, planting it and mapping its position precisely. On another visit, the robot could assess weed populations. On identification, non-competitive weeds could be left and harmful ones removed either mechanically or by a precisely placed micro-droplet of a nanoherbicide. Plant health monitors could assess the nutrient status of individual plants by reading the nanosensors in the crop leaves and apply and activate nanonutrient capsules, and similarly with pest and disease threats.

Vertical Farming.

Vertical Farming is an example of a different aspect of biosystems engineering in which a range of technologies has combined to give a potentially viable outcome.

The picture at fig. 6 shows leafy salad production in a ‘vertical farming’ installation. Installed in 2009, this pilot-scale project is located in the grounds of the Zoological and Botanical Gardens at Paignton in Devon and provides fresh leafy food for the resident animals, particularly primates. It is a working example of a technology with exciting opportunities, especially when integrated with a range of other technologies and related to a set of pressures, all of which can combine to deliver a viable outcome[14].

Fig. 6 Growing leafy salads for inmates at Paignton Zoo.

In simple terms, vertical farming is arranging layers of production on top of each other. In the example here (fig 6), there are eight layers of trays hanging in a stack from an overhead tracking system. The 70 hangers move slowly round the glasshouse passing an automatic watering and feeding station and a harvesting station as they do so.

There is no absolute limit to how high an installation could be, it will be influenced by all the other factors surrounding it, like engineering constraints, location, light, environment, nutrition, harvesting and so on.

The obvious application for this concept is where space is limiting and the food produced is perishable, costly to transport and very close to the point of consumption. Production can be highly controlled, making use of hydroponic and aeroponic nutrition. Similarly the growing environment can be tightly managed in a sealed building, where temperature, humidity, gas levels, air movement and light quality can be controlled and pests and diseases excluded.

There is an obvious cost disadvantage to this system, but many environmental scientists are developing synergies which have the potential to combine to deliver a viable outcome.

Consider the following:

- grow crops in layers to maximise the use of three dimensional space
- grow in a sealed environment, removing the need for any agchems
- provide a controlled atmosphere utilising waste heat from nearby and gas filtration to give the correct air quality for plant growth
- feed and water in a highly controlled way using hydro and aeroponics with no need for a root substrate
- gather and ‘concentrate’ natural light, add light by capturing sunlight energy and then use LED technology to provide light where and when needed
- recycle water from nearby
- recycle nutrients from nearby
- no bulky inputs
- robotic harvesting from a static point, the plants come to the harvester
- programmed production, fresh every day, or hour

- with no root substrate, harvest with the roots attached to preserve freshness and flavour
- provide to customers within minutes of harvesting.

It can be seen that many technologies need to combine to achieve the outcome suggested. All of those technologies exist, it is merely a matter of developing them. The outcome has to be alluring in the context of an increasingly urban population.

Fig. 7 Vertical Farm in a cityscape – fantasy or rational solution?

Soil Science.

Introduction.

The soil is one of the most essential components for sustaining life on earth. Developing our understanding of it should enjoy a high priority. It is a paradox therefore that very little work has been carried out in this field in the UK since the mid-1980s.

The basics of soil mineralogy, chemistry and physics are reasonably well understood but the effects of changes in agricultural practices in recent decades have not been objectively examined[15].

The pattern of arable farming in the UK has changed dramatically in the last 30 years. In 1980, 100 hp was a big tractor and 1,000 acres a big farm, fertiliser and chemical regimes as they might be recognised today had only been widely used for 15 years or so.

Thirty years on, a big tractor is 600 hp, and land operators work over very large areas with heavy machines. High input regimes have been running for 40 years or more. Yet there is uncertain knowledge of how soil physical and chemical characteristics might or might not have changed in that time. There is some evidence that soil bulk density is increasing and soil carbon levels falling. It is not known for sure because objective assessment has not been made.

The last 30 years have also witnessed a dramatic shift in environmental expectations. In the 1980s little attention was paid to diffuse pollution and the effects of farming practices on the wider community. There is now, quite correctly, a keen interest in farming's impact. The Water Framework Directive is being implemented and sets out to ensure that the water environment is properly protected. This has significant implications for UK farmers, affecting all aspects of production management. The soil is a common component in these matters. Many of the potential pollutants from farming enter the environment through the soil, therefore farming's impact on the wider environment starts with the way the soil is treated and understanding its mechanisms is consequently vitally important.

Over this time an arable agriculture has developed which has successfully by-passed the soil's biological processes. Big machines, mineral fertilisers and agrochemicals have supported the growth of a mono-culture based farming system, reliant on fossil fuels and regarding the soil as little more than a medium in which to anchor plants. Against this background it is not surprising that soil biology is also an area where knowledge and understanding is incomplete.

Two branches of soil science are considered here, soil carbon (biochar) and the soil biota.

Biochar.

Biochar is formed by burning carbon based material in an oxygen-limited environment, a process known as pyrolysis (Fig. 8). It is a form of charcoal and is very stable when incorporated into the soil, having a half-life measured in hundreds of years. Claims are being made for both agronomic and environmental benefits[16]. A great deal of interest has been stimulated and much work is being done across the world to improve knowledge of it and how it functions.

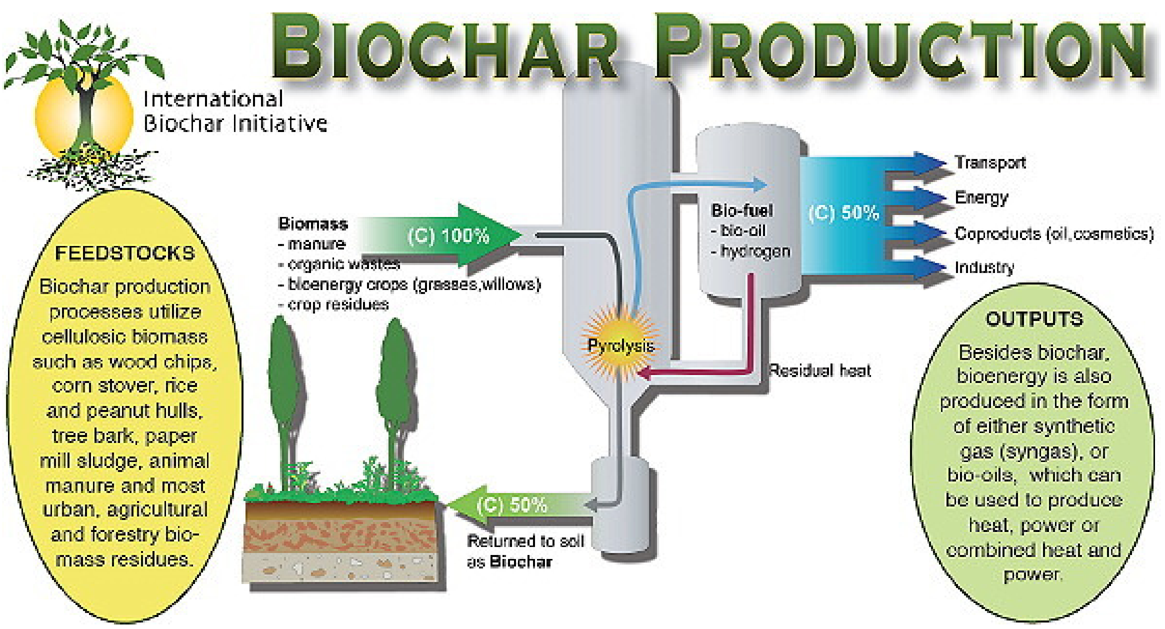

Fig.8 Pyrolysis.

Dr. David Laird of the USDA National Laboratory for Agriculture and the Environment based at the Iowa State University at Ames, USA, is a prominent worker in understanding biochar. He describes it as being like 'the coral reef of the soil', providing a stable and lasting habitat for soil microorganisms, a sponge for water and a structure for holding micronutrients.

Environmental benefit is based largely on the sequestration of carbon. The stability of the product makes it potentially very attractive as a mechanism for capturing and holding carbon in a highly stable form (Fig.9). The pyrolysis process itself results in the release of hydrocarbons which can be captured and refined as bio-fuels and so the whole process can be woven into an integrated biomass recycling system.

Fig. 9 Biochar as fine granules.

The physical structure of biochar is characterised by micro-pores (Fig.10) which provide a good habitat for soil microbes and enhance the soil water holding capacity of the soil. Thus the agronomic benefits case is built on enhancing soil biological activity, increased nutrient holding capacity and increased water holding capacity. It can also influence the physical characteristics of a soil, all of which contribute to it being described a good 'soil conditioner'.

The potential benefits are alluring and it is no surprise it is attracting such attention as it is. One of the retardants to gaining knowledge is the lack of material to work with. In the UK there is now a pilot plant at the University of East Anglia producing 300 tonnes per year for experimental purposes[17].

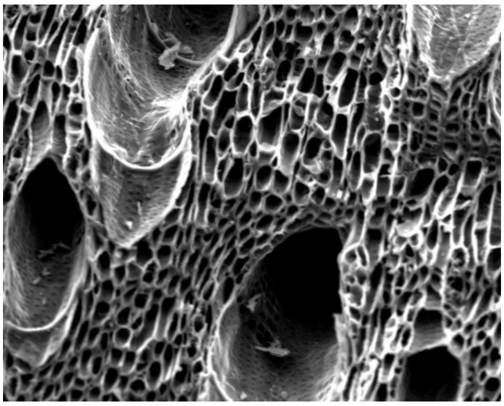

Fig. 10 Biochar under the microscope.

The cost to benefit case cannot be made because it is not known what a commercial plant might look like or cost to run. Neither is it known what kind of biochar is best, the pyrolysis process itself can be varied to influence the characteristics of the outputs, as can the feedstock. It is suggested for example, that pig manure can be pyrolised to produce fuel for jet engines[18].

Amongst the unknowns for biochar is the behaviour of potentially toxic elements (PTEs) in the presence of biochar. It is known that PTEs can be held in biochar and there is some concern that there could be unwanted capture, build up and release of these within it.

Some of the key unanswered questions are:

- Can a pyrolysis plant be designed to produce good biochar and quality biofuels simultaneously?
- How does the biomass feedstock influence the process and the outcomes?
- How does biochar quality influence crop productivity, soil and water quality and carbon sequestration?
- Does the presence of biochar in a soil change the best way to manage it?
- How long does biochar really last?
- How does it stack up commercially?

The Soil Biota.

Soil is much more than a collection of minerals or a sponge to hold nutrients and water. It holds a treasure trove of life - the soil 'biota' – a term which describes everything living thing below ground, from moles to amoebae. In a healthy arable soil there will be well over 10,000 species of living organisms, the most numerous being microbes such as bacteria and fungi. Professor Karl Ritz, Chair in Soil Biology at Cranfield University, describes the soil biota as 'the biological engine of the earth'[19]. He explains that soil organisms drive many of the key processes belowground, such as the carbon and nutrient cycles, on which crop production depend. Furthermore, the soil biota is intimately involved with the control of crop pests and diseases and with forming mutually beneficial relationships between plants and their roots. With a better knowledge and understanding of the myriad of life in the soil, there is a huge potential to unlock an opportunity to work with nature, not against it.

In a healthy arable soil between 0.25% and 2.5% of soil mass (fresh weight) will be living material. This living material is typically made up of:

- bacteria and fungi 10,000 spp
- protozoa and nematodes 100 spp
- insects, arachnids, molluscs and other invertebrates 100 spp
- mammals
- plant roots.

The relationship between a plant, its roots, the soil and soil biota is particularly interesting. This area immediately around a plant root is known as the rhizosphere.

It is known that most plants form intimate relationships with soil microorganisms from a very early stage of growth. Every plant species exudes a unique signature of compounds from its roots which in turn determines the microbial community around it. Vesicular arbuscular mycorrhiza (VAM) fungi form especially intimate relationships with host roots and these are critical in the early establishment and growth of the plants[20].

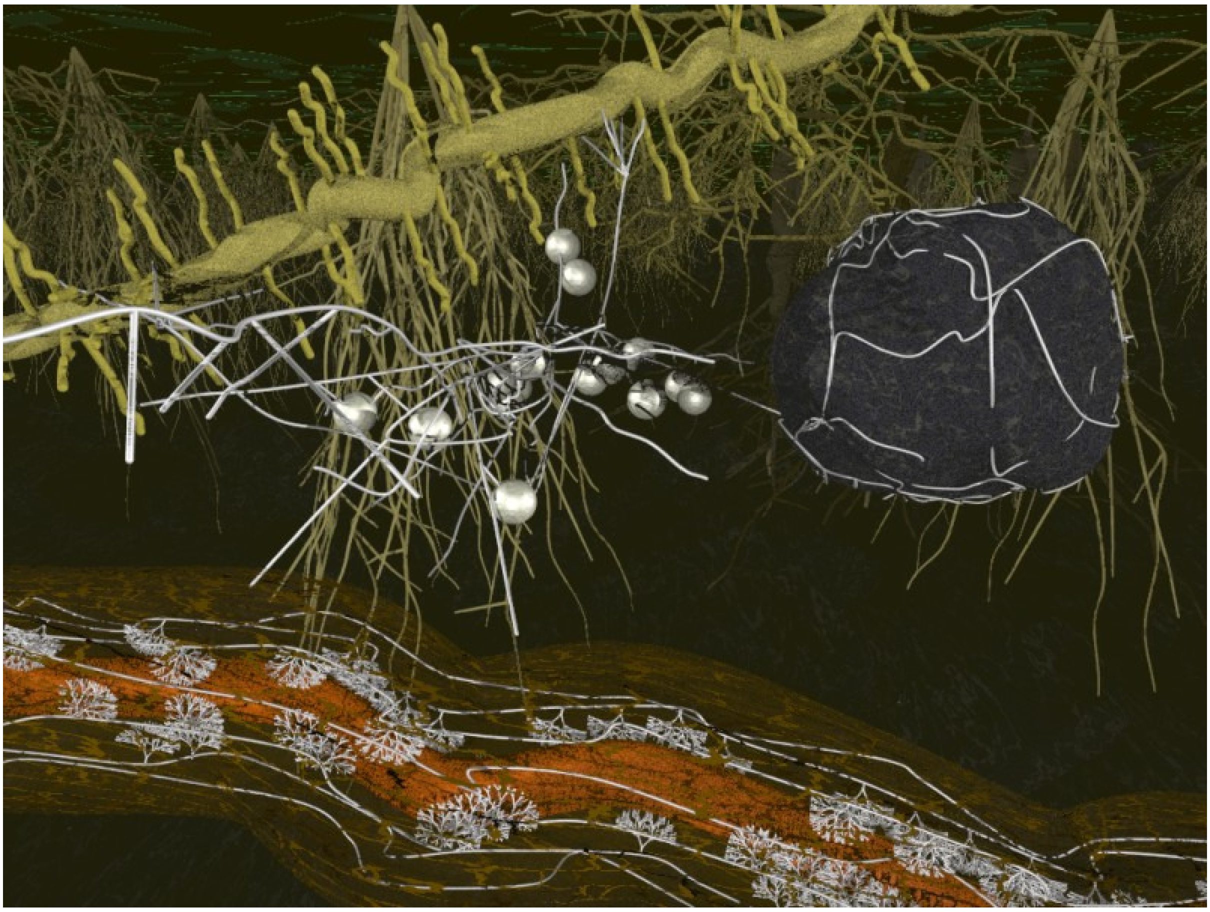

Fig.11 Representation of mycorrhizal fungi on plant roots.

Living in the soil, VAM Fungal hyphae invade the internal cell structure of the root without harming it, forming a mutually beneficial linkage, providing a 'pipeline' through which nutrients and water can pass. In return for nutrients and water, the plant provides carbon-rich photosynthates which the fungi cannot produce for themselves. The fungi facilitate the plants' uptake of water and nutrients including nitrogen, phosphorous, calcium, zinc and copper.

Other micro-organisms break down and recycle organic matter in the soil, detoxifying harmful compounds and releasing nutrients for plants to use.

There are mycorrhizal fungi which form a protective web of hyphae around root hairs, preventing attack by soil borne pathogens.

Bacterial and fungal feeding nematodes can produce antibiotics and toxins which remove competitors in the rhizosphere, and can also produce growth promoting exudates and facilitate soil processes which increase the opportunity for nutrient scavenging.

Microbial excretions aid the formation of soil particles and aggregates, improving soil structure.

There is a vast amount of microbial activity in a healthy soil, some of which is understood. Much is not.

With a greater understanding of soil microbiology and soil-plant-biota relationships, then it is likely that improved crop performance could be achieved. These relationships can be highly host-specific. If the signalling mechanisms were understood, then it is possible that genetics could assist in conferring a beneficial relationship on other plant species.

Genome studies will be essential in this process. Plant genetics will help identify the mechanisms by which plants attract or stimulate given soil biota and thereby open the way to modifying those signalling systems.

Understanding the genetics of the biota is more complex. Many of the microorganisms cannot be cultured in isolation, making species genome profiling very difficult. Metagenics, which is the process by which the gene sequencing of a 'soup' of species is profiled, will eventually reveal a great deal of knowledge of how these microbes work and ways in which they can be manipulated to improve crop plant performance.

Examples of areas where a better understanding of the soil micro flora and fauna could result in improved crop performance:

Water and nutrient efficiency – find species which are good scavengers of water and nutrients, can they be made to work with other crop plants?

Disease resistance – natural protection of root hairs by fungal hyphae, can this be adapted?

Rotational decline – why do crop yields sometimes decline with multiple cropping?

Crop establishment – how are crop establishment and final yield influenced by soil biota relationships?

Plant Science.

Improving the performance of crop plants can involve many branches of science but the most significant is that of breeding and genetics, and here, time scales are highly significant. There are perhaps two distinct stages which can be highlighted.

The first concerns genome knowledge and identifying gene sequences responsible for a particular trait. The second looks at taking that identified trait, embedding it in potentially commercial varieties and finally field testing of varieties for commercial use.

New technology can help to speed up some parts of the process, but other parts remain fixed, for the time being at least. So a novel trait announced today is unlikely to be seen as part of a commercial variety for at least 7 to 10 years[21].

Fig. 12. Arabidopsis, Brachypodium and wheat plants. Brachypodium provides a bridge between the well-characterized Arabidopsis reference plant and key crop plants such as wheat. Credit: BrachyTAG programme (John Innes Centre, Norwich)

Plant scientists use 'model' or 'reference' plants to establish the basic layout of genetic function (fig.12). The model dicotyledonous plant is Arabidopsis, a member of the cress family, chosen for its relatively small genome and its known diversity of form across the planet. Brachypodium fulfils a similar function as a monocotyledonous reference, bridging the gap to the known crop plants like wheat.

The scientific basis of plant genetics has moved greatly in recent years with the development of base-pair sequencing of genetic material. With this knowledge it is possible to work out which parts of the genome are likely to be involved in a particular trait, and to use that information to identify and select individual plants carrying desirable traits. It is now the case that genotype study is working in much closer connection with phenotype observation in the breeding and selection process. Mapping the base pair sequence is time consuming and costly. It is also only the first step of a hugely complex process of working out the function of pairs and sequences. Computer science and statistics now play a large part in plant breeding.

Fig. 13. Monsanto seed chipper.

At their headquarters in St Louis, Missouri, USA, Monsanto have developed and operate a facility for laboratory selection of maize and soybean seeds based on their genetic make-up. The so-called 'chipping' process takes a small slice of the endosperm of a seed grain and analyses the DNA within it, looking for particular sequence matches (fig. 13). Seeds carrying the desired matches are retained and grown on, those remaining are discarded. This process is highly automated and can screen many thousands of individual seeds per day. It replaces the much more time consuming and costly process of growing all of the seeds into plants and then looking for the desirable traits. Key to the success of this technique is the ability to take a slice of the seed without destroying the germplasm. The concept is valid for any seed. The problem is developing techniques to take a DNA sample without damaging the seed's ability to be grown on[22]. Techniques like this one greatly reduce the resources and time needed to select and multiply breeding lines and are contributing not only to speeding up the development of new lines, but also to reducing the cost which means that breeding and selection input into more minor crops, including vegetable and salad crops, becomes commercially rational.

There will be interactions and links with other technologies which will influence the path of crop plant development. For example, the more we understand about the role of the soil biota in disease resistance, the more precisely we will be able to manage the genome of the crop plant to exploit that knowledge. Similarly, the more we understand about nutrient capture and transport in the rhizosphere, the better able we will be to develop varieties to complement that activity.

Looking at the relationship between plant genetics and biosystems engineering, there are huge overlaps where the progress of one technology will influence the other. For example, when we have smart machines capable of controlling weeds at the individual weed level within a crop stand, then we will be less concerned about herbicide tolerances and sensitivities in crop plants.

Historically, plant breeding has not concerned itself with water and nutrient efficiencies, resulting in profligacy in these traits. The major targets for breeders have been yield, disease resistance and some quality and agronomic traits. There is no doubt this is changing. Primary research in plant genomics is focusing significantly on aspects of frugality and this begins with developing an understanding of how water and nutrient cycles work at the genome level.

Plant scientists and geneticists around the world are working on a vast range of traits which have the potential to transform production outcomes for farmers, but it will be at least 10 years before any of them reach the market, and more probably 20 to 30 years. A list of examples:

- Improved nitrogen efficiency.
- Nitrogen fixing – a 'Holy Grail' of plant breeding! Known to be genetically very complex and energetically inefficient it nevertheless remains the target of much work and if successful, will have a role in a nitrogen-stressed environment.
- Water efficiency and saline tolerance – genes have been found in a relative of wheat which work by excluding sodium, preventing it from passing from root to shoot tissue where it becomes toxic[23].
- Timing of flowering – the genetic triggers of flowering are becoming better understood which may result in, for example, an ability to programme a range of flowering triggers in crops like broccoli, to give a succession of maturity dates across a growing season. It might also permit the manipulation of flowering time to coincide with more favourable flowering and grain-fill periods[24].

Fig. 14 Broccoli – manipulation of flowering could allow new ways of sequencing maturity dates.

- Optimising of grain shape – modifying the shape of a wheat grain to remove the crease could give significant gains in milling performance and flour recovery.
- Rhizosphere relations – this links closely with the section on soil biota and illustrates the need to consider these branches of science in parallel. Understanding one strand of the science will be the key to progress in another.
- Environment sensing by plants – it is known that plants respond to a range of environmental factors like temperature, day length, moisture stress, nutrient stresses. If these sensing mechanisms were better understood, they might be modified and manipulated to change various trigger points, for example, using temperature sensing to change flowering time, or breeding plants tolerant of temperature stress.

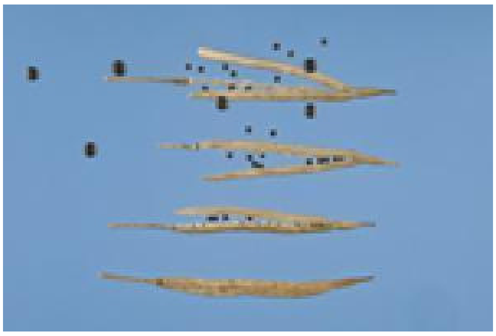

Fig.15. Understanding pod shatter mechanisms could reduce yield losses in brassicae seed crops.

- Pod shatter in brassicae – it is now known that gene–switched hormone production governs the way in which brassicae seed pods open to release the seeds. Through better understanding this could be manipulated to reduce harvest losses in oilseed rape crops[25].
- Mycotoxin reduction and ethylene signalling – fusarium infections in the UK wheat crop are particularly damaging, especially as the fungus produces a mycotoxin, deoxynivalenol (DON), which accumulates in the wheat grain. Genetic linkage between ethylene signalling systems in plants and susceptibility to fusarium infection have been found and are being incorporated into plant breeding programmes.

- C3 vs. C4 photosynthesis – most crop plants photosynthesise using the 'C3' pathway which is an energy efficient but water profligate adaptation for temperate conditions. However, under high light and/or low water stressed environments, the 'C4' pathway is better. C3 relies on an enzyme which fails under high radiation, causing the plant to respire, thus reducing the rate of photosynthesis. The C3 pathway also requires carbon dioxide to enter through the stomata which in turn results in high water loss. Developing plants able to grow in UK conditions using the C4 pathway would result in greater water use efficiency and improved photosynthesis at high temperature and light levels. These pathways are genetically highly complex, but in the case of wheat, wild relatives are known to exist which are C4, so it might be possible to produce C4 wheat one day[26].
- Root hairs and phosphate recovery – one factor regulating root hair growth in wheat and barley is now known to be a genetic switch in response to hormones triggered by low levels of phosphate in the soil. Understanding this switch could open the way for more efficient phosphate scavenging and growing of crops in very poor soils[27].

There is a definite development 'pipeline' at work with new varieties of crop plants constantly coming forward. Conventional breeding will continue to deliver incremental improvements in yield potential, quality traits and pest and disease resistance. Taking the example of wheat in the UK, the average yield is currently about 8t/ha, industry leaders are achieving 12t/ha and the peak yield is 18 t/ha. This would suggest there is plenty of scope for improvement just by honing best practice and better understanding of the variables. It is worth noting that in the past 10 years the improvement in genetic potential has not been expressed in the field, suggesting that there are factors at work which are depressing yield expression.

Transgenic techniques (moving genetic material from one species to another, often referred to as GM or genetic modification) have not been considered here. They remain a high risk option for large parts of the world, especially NW Europe, but at the same time have demonstrated huge benefits with massive uptake in some crops in some areas. There is undoubted frustration within the scientific and commercial communities regarding public resistance to this technology.

Mutagenic modification was first observed 70 years ago and describes the natural process of genes changing by mutation, i.e. random and unpredictable changes in genetic makeup. Plants have a mechanism by which they can 'repair' minor irregularities and this ability has been exploited to speed up the process by which traits can be made to be expressed from within the plant's own DNA. Cibus Global, USA, has recently been granted an EU patent for its RTDS technology (Rapid Trait Development System^{TM}) to introduce glyphosate resistance into crop plants[28].

Marker-assisted selection will underpin developments in crop varieties for the UK until such time as the transgenic debate is resolved. It is evident that many valuable new traits are being developed for crop plants and will benefit the UK agri-food sectors.

Case Study - Wheat Breeding. UK arm of French based RAGT seed breeding company is actively working to understand the relationship between plant roots and soil mycorrhiza, looking for genetic links to disease resistance and nutrient uptake. This is in direct response to EU directives limiting access to chemical fungicides in the medium term, and recognising a need to exploit natural plant – soil – mycorrhizal symbiotics in the long term. It is hoped that this work will eventually lead to plant varieties which rely far less on the agrochemical inputs of today's varieties. It is further hoped that the work being done now on wheat plants will be transferable to other crop plant species.

Water.

Introduction.

The water requirements of agricultural systems in the UK are largely rain-fed. The combination of a moisture retentive soil and a steady rainfall pattern results in most crops having access to a sufficiency of water for most of the growing season. Short term surpluses and deficiencies (floods and droughts) will influence crop performance but in the majority of situations the economic cost of irrigation is not balanced by the gain from any improvement in performance.

In areas where irrigation is widely practised the typifying features are a combination of free-draining soils with a low water holding capacity, low summer rainfall and moisture sensitive crops.

The environmental pressures currently at work suggest that in the UK the fresh water resource will be considered increasingly scarce. It is also likely that as time passes, more crops will fall into irrigation need, especially if the predictions for rainfall are correct. For agriculture to respond to this it must find ways of:

- Increasing the ability of soils to retain moisture and to give it up to plant roots.
- Develop plants which are more water efficient or can tolerate short term environmental perturbation without permanent damage.
- Develop plants able to tolerate water of lower quality without suffering yield or quality penalties.
- Apply water more accurately and efficiently.
- Reduce the energy and other resource requirements of irrigation.
- Reduce diffuse pollution impacts of irrigation.

There is considerable cross-sector response to meeting these challenges.

Developments.

In soil science, work on soil biota, reduced soil-disturbance techniques, soil organic matter and biochar will lead to a greater understanding of soil water relations. Creating soil structures with a greater water holding capacity will increase the size of the natural buffer system which in turn will determine the requirements of irrigation systems and plant biochemistry.

Plant scientists working at genome level are discovering genes[29] which equip wheat plants to survive short-term water or heat stress. Crops with these traits will be beneficial in environments where irrigation is either not possible or not economically sustainable, surviving extreme events which hitherto would have resulted in crop failure.

This report has already highlighted successes in isolating saline tolerance[23] in crop plants. Crops which can deal with or otherwise filter out toxins in water would be advantageous. Using another technology, it is possible that nanotechnology could provide answers with water filtering and purification in the growing medium.

Work continues to extend the understanding of water use by plants and to find genes which confer reduced water profligacy. There are known links between root drought stress, plant hormone production and stomata control which are exploited in so called 'partial rootzone drying' (PRD) techniques[30] for irrigating multi-annual crops. (Fig. 16)

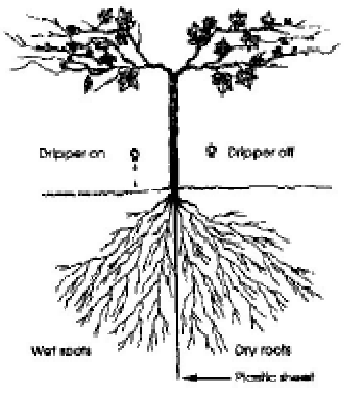

Fig. 16. Partial rootzone drying of multi-annual crops, two independent water supplies supply the two sides of the root system so that each half is alternately wet and dry. The drought stress condition stimulates hormone production which causes the plant to close stomata in the leaves. Water efficiency increases disproportionately to yield or growth depression, giving a net improvement in efficiency of water use.

In biosystems engineering, the timing, quantity and delivery of irrigation water is the target of many studies. A number of techniques for assessing plant need for water are being evaluated and developed. Photographic and thermal imaging can show where water stress is developing and telematic systems are being developed to gather and interpret information and then direct irrigation equipment automatically.

Developments in Pig Production.

Introduction.

The first draft of the pig genome was released at the Wellcome Trust Sanger Institute, Cambridge on 2nd November 2009[31]. Nineteen institutions across the world were involved in funding and supporting the work. It took five years to complete and cost £15m. The sequence is in the public domain with no proprietary interests permitted and it will help researchers pinpoint genes useful for pig production. It will also help with human medical research because people and pigs are very similar in their physiology, behaviour and nutritional needs.

Fig. 17 Lawrence B. Schook, right, a professor of biomedical sciences at Illinois, with animal sciences professor Jonathan Beever. Schook, who is also an affiliate of the Institute for Genomic Biology at Illinois, led the international pig genome sequencing project, which has produced a draft of the pig genome. (Credit: Photo by L. Brian Stauffer, U. of I. News Bureau)

Genomes and Gene Marking.

Gene marking techniques are well established in animal breeding, especially in the cow where the release of the fourth draft of the genome is imminent[32]. Marker density in the cow genome is now an average of one marker per 10,000 base pairs, compared to 1 marker per 3 million base pairs on the first release in 2004. The marker density is an indicator of the expansion of knowledge of base pair sequences and their likely linkage to phenotype traits.

One area where this technology is already evident is in the speeding up of evaluation in breeding programmes. The American Angus Association offers its members a genomic profiling service where the DNA of young animals can be compared to breed standards and predictions made on a range of production and carcass traits[33]. Through this process, farmers can gain early indication of the likely potential of breeding animals, with obvious benefits of time, cost and performance.

In the pig sector in the UK, commercial genetics providers like PIC are increasingly using marker technology in their breeding programmes[34]. Genome based techniques are particularly useful in developing traits which are difficult to observe or measure in the living animal. Meat quality traits like marbling and loin depth fall into this category. Prolificacy is not highly heritable, so gene marking can help unravel the complex nature of its genetic drivers.

There is a growing interest in the pig gut biome. As with soil microbial populations, it is difficult to isolate and culture individual species outside the host. Metagenic techniques are being developed to understand the complex relationship between the host and its gut biota. Sequencing the collective DNA of the microbial 'soup' will eventually reveal the identity and activity of the thousands of microbe species in the gut biota. There are many interactions leading to a wide array of outcomes[35]. Gut biota/host interactions are thought to influence a range of biological processes, including immune system responses, disease resistance, fibre fermentation, food utilisation, ammonia and greenhouse gas production, and fat and muscle deposition. There is no doubt this is an important area of animal science and will lead to significant increases in performance as knowledge grows and is incorporated into commercial breeding lines.

Welfare.

Development work is not confined to genetics. Danish workers[36] are investigating a spread of welfare based topics including rooting behaviour, housing and sow management. Ways are being investigated to enable the sow to take better care of her young, seeking benefits from increased milk uptake and piglet uniformity, health and performance.

Biosystems Engineering.

Biosystems engineering is also playing an increasing part in the sector. Visual image analysis techniques are being developed in the UK to remotely monitor growing pigs (Fig. 18). Using cameras fitted over feeding stations, the system measures the changing outline of three areas on the back of the pig. This data is fed back to a central computer which translates it and reports it in a graphical form[37].

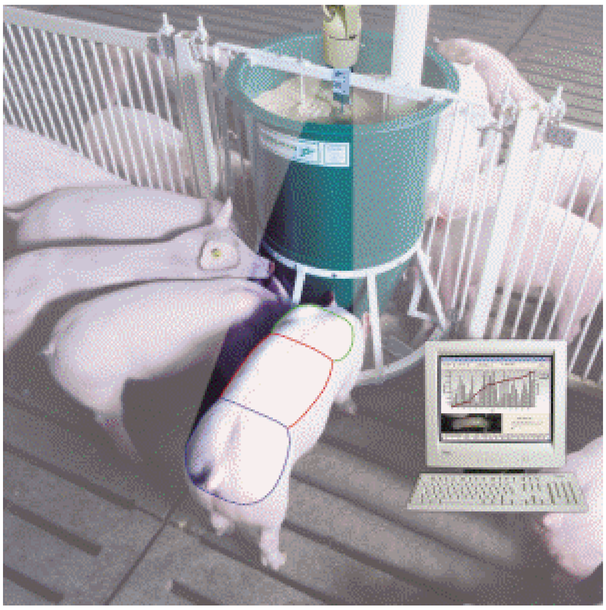

Fig. 18 'Vista' is a visual system for monitoring a pen of light coloured pigs. It can be used in commercial growing / finishing operations to automatically determine the weight distribution and growth rate of the pigs in the pen.

The UK Sector.

There are a number of characteristics of the UK pig sector which lend it to being an early adopter of new technology:

- It is a professional and committed sector with over 80% of production in the hand of fewer than 20% of operators.
- There is a tendency for pig producers to be specialists, so they are focussed and less likely to be distracted by or drawn to alternative activities.
- The sector knowledge transfer network, based on the BPEX[38] and NPA[39], is well established and supported.
- Genetic improvement is highly commercial and embedded in global players, the leaders being of UK origin.
- It shows a good record of development with straight-line improvement in key performance indicators over the last 50 years.

Improvement in Pig Sector Performance 1960s to 2005.

	1960s	2005	% Change
Pigs weaned.sow^{-1}.yr^{-1}	14	21	50
Lean meat %	40	55	37
Kg lean meat. tonne feed^{-1}	85	170	100

Source: Modified from van der Steen, Prall and Plastow, 2005 J.Anom Sci 83: E1-E8

There is every indication that the steady improvement of the past half century is set to continue for some time to come. The difference in performance between the upper quartile and the remainder of the cohort shows room for growth, but there is a need to continue to feed innovation into the development pipeline to maintain progress.

Conclusions.

This study has highlighted a significant amount of new work being done over a range of disciplines. The global scientific community is close-knit with many projects involving wide international collaboration. Researchers and scientists themselves are often well travelled, having worked in a number of institutions in different countries. This has led to a well established network where many of the participants know each other and have probably worked alongside each other as well as collaborated at great distance.

The UK is particularly strong in fundamental genetics and is at the heart of many international initiatives. Institutions such as the John Innes Centre, Food Research Institute and the Wellcome Trust Sanger Institute are world leaders in their fields.

In contrast, biosystems engineering is particularly weak in the UK with little direct investment in new work. That said, some of the most innovative scientists in this field were part of the engineering research establishment at Silsoe, Bedfordshire prior to its closure. They have maintained their commitment to their craft, albeit on a more independent basis and are behind some significant developments in robotics, vision systems and sprayer technology.

Soil science, especially biology has been neglected by the developed world but there is strong evidence of this changing. Now that environmental impact of farm production has raised its profile, more attention is being paid to this area.

Of all the factors highlighted in John Beddington's 'Perfect Storm', water is the most vulnerable, probably because as a problem, it is the least visible to those in the developed world. Western cultures seem to have embraced the importance of maintaining biodiversity, conserving energy and securing food supplies, but a disproportionately small amount of effort is being expended in understanding water.

The integration of technologies is highly evident. Plant breeding is now dependent on information technology and statistics as much as biology and genetics, leading to the coining of new terms like 'bioinformatics'. Biosystems

Engineering recognises the link between engineering sciences and biological sciences when considering mechanisation of crop related activities.

Nanotechnology is already impacting significantly and will continue so to do. By its very nature and definition, it will appear in every field of human activity, including farming and food.

Introducing new science will be an evolutionary process requiring innovative input at all stages. The uptake of new ideas will only happen if the incentive package is correct. This might be led by regulation, by commercial pressure or a combination of the two.

The need for science to develop solutions to avert the worst effects of the Perfect Storm is already evident in the range and scope of work being undertaken around the world. Science and technology are making plants and animals genetically higher performing and more efficient, the means of production are becoming less energy and input consuming and ways are being found of combining sciences to deliver novel solutions.

There is a very strong likelihood that through science and technology, the farming and food sectors will be able to deliver what is required of them in meeting the challenges of 2030 and the gathering storm.

Recommendations and Actions.

There is a need to re-invigorate the partnership between science and agriculture. Professor David Leaver makes this case very well in a recent paper prepared for the Practice with Science group of the Royal Agricultural Society of England[40] in which he argues the case for a competitive agricultural industry to meet the future challenges of food production and land use.

The UK cannot rely on other countries for innovation and should develop its own capability through public and private partnership.

Public investment in recent years has centred on fundamental research, with qualified success. The public sector has largely withdrawn from applied and near-market research resulting in a great fracture in the innovation chain. The private sector has failed to bridge the gap between primary research findings and useful outcomes for industry. Consequently, new science is not finding its way into the commercial arena and there is a 'disconnect' between farmers, developers and pure scientists.

The recently reformed agricultural industry levy bodies under the umbrella of the Agriculture and Horticulture Development Board (AHDB), represents a unique opportunity to set out and encourage a new innovation platform for science and farming. Having appointed their own Chief Scientific Advisor[41], the AHDB has sent out a very strong message about the place science has in its work and is well placed to influence the wider scientific community and to lead the levy payers it represents.

Through their levy bodies and the AHDB, farmers should encourage and take part in initiatives to bring new science from the laboratory through the development process and onto commercial units. Primary researchers should be encouraged to engage in more 'use-inspired' work to facilitate development of outcomes of more immediate value to end users.

Organisations like the AHDB have an important leadership role to play. A large part of this is encouraging their levy payers to take 'ownership' of the innovation process, to take part and positively engage.

The John Innes Centre in Norwich is a world class biosciences institution and has a pro-active programme of reaching out to anyone interested in its work. Through the 'Friends of JIC' network, people can visit the Centre, talk to researchers and debate the issues[42]. This accessibility is important and should be replicated throughout the innovation and development chain. It should also be two-way. It is just as important for scientists to understand the fundamentals of farming as it is for farmers to have a basic understanding of science. Only then can the right questions be asked of each other, debates held and research priorities assembled.

The position of agricultural science on the curriculum of higher agricultural education should also be reviewed. Employers of agricultural graduates should be lobbying for a good base knowledge of scientific principles in employees. This is not only important in establishing the status of science in the minds of new entrants, but also in equipping those people to take and use that understanding to encourage ongoing and appropriate scientific development.

There are many ways in which the various parties can work towards bringing new science and technology into farming and food. Some have been discussed here.

Re-invigoration of the science and farming partnership is vital to a successful future for all, but it will only succeed if the outcomes are relevant, achievable and commercially sustainable.

Ten action points to deliver new science to UK farmers and food sectors:

1. Seek involvement and engage in the technology process.
2. Meet with and talk to researchers, invite them to your farm, visit them in their laboratories.
3. Use the AHDB and find out where your levy is being spent and what on.
4. Use Technology Strategy Board funding to develop projects, find suitable partners and collaborators to help bring ideas forward.
5. Lobby for agricultural science to be given a higher priority in the higher education curriculum, begin with your own alma mater, find out what it is doing in this area.
6. Check your own knowledge of science, if you find it wanting look for short training courses to give you a top-up, and if there is nothing 'off the shelf', look to your local training provider to put something together for you. Remember, a basic understanding of science will help in asking the right questions.
7. Biosystems Engineering is particularly lacking in UK Universities. Harper Adams is to be congratulated for re-invigorating its own BE department and we should support them and encourage other faculties to develop similarly.
8. Guidance systems and telematics are vital to agricultural technology development, push for the establishment of a countrywide, robust signalling system.
9. When investing in new plant and equipment, look carefully at the technology available and think about value as well as cost.
10. Keep your decisions commercially sound and technically sustainable, they must be right for your business.

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