Journal of Agricultural Science (2011), **149**, 55–61.
doi:10.1017/S002185961000095X

FORESIGHT PROJECT ON GLOBAL FOOD AND FARMING FUTURES

Engineering advances for input reduction and systems management to meet the challenges of global food and farming futures

W. DAY

Harpenden, Herts, England, UK

(*Revised MS received 11 October 2010; Accepted 11 October 2010; First published online 19 November 2010*)

SUMMARY

Improvements in farming systems and food supply will come from: increased production efficiencies per unit land area or per unit input of key components such as water or fertilizer; from less negative impact on local and global environments, allowing sustainable biodiversity goals to be integrated with production performance; and from enhanced approaches to bringing global supply and demand in balance, allowing internationally agreed goals for biosphere stability to be shaped, managed and delivered. Each stage will deliver significant improvements to current farming approaches. Modern engineering methods and technology advances have enhanced productivity in all major industries, and farming is yet to make much progress by developing and adopting these technologies. Sensors, control and integrated management systems will be major features, delivering enhanced farming productivity per unit input and per person employed, complemented by decreased environmental impacts and lower losses in the food chain. New insights into modelling and interpreting systems' performance will provide key contributions to optimization and control under complex challenges.

THE CHALLENGES AND DEMANDS FOR ENGINEERING ADVANCE

The challenges to farming efficiency are:

- Increased efficiency in resource use, including light conversion into biomass, carbon productivity per unit water consumption and net greenhouse gas benefit (net consequence for global warming of emissions of N_2O, CH_4, etc. less CO_2 fixation) per unit production.
- Minimization of non-productive losses from farm to point of use, whether this is as energy or as food in the market place.
- Increased control of the performance of complex systems, through precision interventions or control actions that respond to direct observations of system performance or estimates using surrogate signals and system models.
- Better balance of productive outputs and sustainable natural systems, maintaining soil organic matter, minimizing soil damage and water pollution, etc.

Engineering and physical science will provide key understanding and technologies to meet these challenges. Technologies must work in harmony with nature, and also draw in the efficiencies of the industrial world in order to address the excessive demand that the human population is putting on natural resources. In the longer term, the demand itself must also be constrained, allowing efficiency goals to be redirected more towards maintaining natural systems and resources and while sustaining outputs of food and feed. It will require greater political will to curb growth in demand and recognize that every ecosystem has bounds that, when crossed,

Email: bill.day@silsoeresearch.org.uk

lead to instability and an enhanced risk of disaster. Restricting population growth, or ultimately reducing absolute numbers, is a challenge that will have to be faced. For now, mobilizing more productive methods is an important strand. Alongside this, approaches that can minimize environmental damage must be developed and applied.

Translation of technology from other industrial sectors will be an integral part of the approach, and should be seen as a positive benefit, allowing the economies of scale in the consumer or transport sectors to be realized in agriculture. New, stronger materials developed for the motor industry will allow lighter farm vehicles and less soil damage. The information technology (IT) sector and space industries will provide capability in real-time data handling, automation and sensing that will be directly relevant to improved management of land areas and production systems.

Fast-developing countries such as Brazil are already adopting technologies that can maximize the productivity of their systems. The integration of better controls, precision technologies and methods that address environmental impacts and sustainability should lead to production advances in sympathy with nature and ensure that new management methods work together with environmental objectives.

The demands for innovation will be diverse, although economic and social measures will constrain uptake of some technologies. Concerns over environmental and biodiversity issues are likely to be at odds with maximal production. Crop productivity per unit land area will be a relevant index for some, while others will be seeking greater productivity per unit water used, higher harvest indices or sustained productivity with less impact on biodiversity in the cropped area. Other integrating measures will grow in importance – outputs can be measured in units of human nutrition or useful calorie intake, and inputs tagged with their total fossil carbon use or the greenhouse gas release during their manufacture (e.g. for fertilizers and pesticides). Integration along food chains and across systems, using life-cycle methodologies, will be particularly important (Gerbens-Leenes *et al.* 2003).

New engineering science will address approaches ranging from holistic methods through to fine-scale technologies. The scientific challenges will reflect the complex biological nature of the underlying processes being managed, which frequently operate under the uncertainty of both environmental and biological drivers. Scientific methods that can capture and interpret variability, and can define near-optimal management approaches, will be important underpinning for the advances in crop production and food chain management.

Business ratios may need to be assessed in identifying how future farming systems will change. The farming businesses of Brazil and the demands on Chinese food production associated with big city growth reflect some of the diversity in the ongoing changes. Productivity per agricultural worker can increase as business investment facilitates higher returns on capital employed. Urbanization will lead to expectations of enhanced quality of employment and remuneration, and ultimately this will require farm employment to involve increased sophistication and skill if it is to compete in the labour market. New tools and techniques that increase productivity can justify capital investment. These concepts involve political issues (including land ownership) that will affect the translation of new technologies into practice.

The efficiency of production in developed countries needs to be enhanced too. Greater levels of carbon fixed per unit fossil carbon used are an essential target, particularly under the competing demands for land from food production and renewable energy generation. Sustainable production systems and methods will be an integral part, to ensure high levels of carbon offtake are not made at the expense of future declines in soil quality and production stability (Dawson & Smith 2007). High energy and emissions in fertilizer manufacture and the impending global shortage of phosphorus fertilizers reflect growing challenges to sustainable systems.

The trends in other manufacturing and production sectors, for example to automation, traceability and better communication with end users and customers, will set key directions for food production. Two factors may act as delays: the complexity of the task with such extensive and variable systems as those in the food chain (Huang *et al.* 2010), and the sensitivity of some groups to taking the tools of the factory into the natural world of food production. Modern engineering tools can also provide the information flows and feedback that will satisfy demands for traceability (Thakur & Hurburgh 2009; Kondo 2010).

The future demands greater use of information and intelligent decision-making, and automation of tasks that feed off this information. Increased productivity is a global requirement to meet food demands, and traceability, sustainability and input minimization set requirements for new science and new technology.

THE ROLE OF SCIENCE AND TECHNOLOGY

The major strands through which new engineering science and technology will contribute include sensing and data acquisition, information interpretation and control, and systems modelling and management.

Sensing and data acquisition

Data acquisition will advance through novel sensors, higher spatial and temporal resolution in measurements, more robust technologies that can be moved from the laboratory to the field, remote sensing, and the ability to store, handle and transmit data more efficiently. The achievement of maximum value from an agricultural production system depends upon making a set of near-optimal decisions throughout the course of the production process. Sensors capable of detecting size or quality factors are critical if control decisions are to be automated, requiring new methods and translation of technologies from other sectors (Wang *et al*. 2006).

Hyperspectral imaging

High-resolution spectral methods that have been developed for satellite remote sensing systems are now showing potential for much more detailed evaluation of physical and chemical status of natural products and systems (Goel *et al*. 2003), including food product quality (e.g. protein levels in grains) and environmental markers (e.g. nutrients in organic manures). The advance of high-resolution reflectance spectroscopy has provided a means to detect levels of key molecules in living material with minimal preparation and outside the laboratory. This opens the door on precision estimation of key aspects of crop status relating to quality and environmental impacts (Hatfield *et al*. 2008). For example, wheat production in temperate climates requires nitrogen fertilization in order to optimize production of bread-making wheat: the nitrogen availability must match the demand of the growing grain at the end of the season. The conjunction of a quality premium (for bread-making) with late-season nutrient requirement has the potential to lead to significant risks of excessive fertilization, enhancing the potential for emissions of nitrous oxide and leaching of nitrates. Management regimes that can minimize these risks can be realized through the effective deployment of sensing methods, such as hyperspectral sensing, to give the information required by crop management decision models.

A significant future challenge will be in efficient use of hyperspectral or optimized multi-spectral sensing methods. The complexity of plant tissue structures and the processes of mobilization and reutilization of nutrients within plants mean that simply sensing the levels of key molecules will not be a direct determinant of performance. A combination of sensing with models of transformations and transport will be needed. It will also be important to establish efficient translation of the identification of key hyperspectral bands into functional practical sensors at specific optimal wavebands. Success with a hyperspectral system in the confines of a research study does not give an immediate route to a robust sensor, cheap enough for mass deployment and optimal in its choice of bands for a variety of biological systems.

Trace gas detection and identification of diseases

The use of real-time monitoring of chemical species in production processes has developed through technologies such as the electronic nose. Real-time sensing of gases using electronic nose technology, based on chemometric sensing, has provided initial insights, although it is dependent on correlations that do not provide tight discrimination in all circumstances. Recent studies using real-time mass spectrometry to measure molecular species concentrations directly are suggesting potential routes to animal disease detection, although specificity is currently a challenge (Spooner *et al*. 2009). For plant disease, the release of specific chemicals at inoculation has suggested that there may be scope for monitoring systems based on the detection of key molecules, although the opportunity may be limited to sentinel plants or enclosed systems such as greenhouses (Jansen *et al*. 2009).

The challenge in taking this forward for the future is at least twofold. First, gas detection is preceded by a phase of gas release and dispersion. Understanding and managing this phase will be critical both to the resolution of the technique and the degree of interference by other factors. The second strand concerns the specificity and sensitivity of the techniques, and this applies broadly across many sensing methodologies. An optimal sensing technique will give high sensitivity even at early stages of the disease progress, such that interventions of whatever type can be triggered rapidly, minimizing the amount of disease that can appear in the population, and potentially allowing lower cost intervention for control. However, high specificity is equally important so that interventions are not triggered unnecessarily. Current sensing technologies demonstrate significant potential (Rumpf *et al*. 2010), but reproducing this with sufficient sensitivity and specificity in practical situations sets a real challenge for the future.

Biosensors for status monitoring

Biosensors can directly detect active molecules in live systems and new sensors will be capable of determining the levels of molecular species that represent critical states in production processes (Velasco-Garcia & Mottram 2003). To date, the major global penetration of commercial biosensors has largely been limited to medical use of the glucose sensor for blood sugar to support diabetes management. This is despite the extensive basic and applied science research programme on biosensors. Market pull and breadth of applicability are critical factors (Luong *et al*. 2008). However, we can expect significant advances in the first half of the 21st century, as the concept of targeted sensing and management develops. An example for agriculture will be better ways of managing dairy herds by monitoring the levels in milk of hormones associated with pregnancy. The principles are established (Xu *et al*. 2005), and with developments in technologies that give robust biosensors, the approach can be expected to aid productivity and reduce culling, as insemination is optimized and knowledge of pregnancy status is improved. The principles of detecting hormonal indicators of pregnancy status in dairy animals or the presence of food pathogens using biosensors (Nayak *et al*. 2009) have been proven at the laboratory level. The translation into realistic components of biosystems management will be an important target in future.

Information interpretation and control

Information interpretation and control will bring together advances in mathematical and statistical methods with computing to provide useful knowledge from increasingly large bodies of data. The large volume of information that is relevant and valuable will demand new methods, particularly building from the concepts of data mining and spatial analysis, to provide input to decision support, management and control systems. Critical to the usefulness of this data will be the rapidity with which it can be gathered and transmitted further. The advances in mobile phone systems and related communication methods will provide effective approaches for wide-scale monitoring of agricultural systems (Voulodimos *et al*. 2010), and communication to farmers for decision support systems.

Control technologies and concepts will provide a major opportunity for new technical approaches to managing productions systems (Dabbene *et al*. 2008). The realization of value may be through autonomous vehicles capable of independent but co-ordinated operations in crop management, through to robots replacing conventional machines and/or people for specific processes in the food chain, from crop harvesting to post-harvest management and processing. Although robots and other automated processes have already had a major impact in manufacturing industry generally, their translation to food and farming systems is proving more challenging because of the unstructured environment of biological production processes and the inherent variability of biological systems.

Spatial variability and optimized inputs

The precision agriculture concept has been under active development for more than 20 years, but the concepts are still in the process of translation from a vision to practical approaches. The prime challenges can nearly all be associated with the chain from sensors and detection through to management and control (Zhang *et al*. 2002). The basic tenet still holds true – managing inputs uniformly across whole fields has only limited logic as soils and topography vary. The spatial variation of weed infestations also demonstrates that herbicide inputs can benefit from spatially targeted control (Slaughter *et al*. 2008).

Progress in this area will benefit from new sensing methods. However, it is also critically dependent on the establishment of appropriate mathematical and statistical approaches that can translate uncertain information about the state of soils and crops into reasoned decisions that can be implemented at critical points in the growing season. There will always be distinct limits to the precision possible in these decisions, given the fact that spatial patterns of crop performance can be inverted between wet and dry years, and forecasts of yield in mid-growing season depend on weather prediction – an inexact science.

The use of geostatistics and other mathematical tools is building the basis for interpretation of variation (Lark & Wheeler 2003). Data on crop status gathered during one growing season and at harvest will underpin decisions in future seasons. At the centre of the decision-making process will be parsimonious models defining the form and scale of responses to individual interventions, such that the principles of decision support can be convincing to the expert farmer and build confidence in advanced approaches (Oliver *et al*. 2010). These methods could be readily developed to optimize not just economic productivity but also productivity constrained by well-defined environmental goals.

Of course, precision agriculture will vary enormously across farming systems. Delivering real value will depend on the identification and commercialization of technologies that can have wide application and establish a competitive market. For example, sensors providing information on nutrient content of manure inputs and harvested grain (see above) will provide scope for improved system control (Sinfield *et al*. 2010).

It is important to note that, independent of spatial variation, accurate prediction of optimal fertilizer inputs for crops at field scale is still a significant challenge (Sylvester-Bradley & Kindred 2009). The introduction of sensing and modelling systems through precision technology will provide parallel benefits by addressing this problem.

Machines optimized for sustainable production

The developments in agricultural field mechanization through the 20th century were dominated by increases in size and scale, and in vehicle mass. The benefits have been in increased work rates and an economical platform for the latest technological developments, whether in tractors and cultivation control or in harvesters of vegetables or grain. However, a significant adjunct to these developments has been increased risk of soil damage through the ground pressure of these vehicles. The advent of the robot has suggested that there might be a niche for small units as well – 'service robots' that can operate autonomously to deliver specific tasks within the field in ways that maximize precision and minimize extraneous damage (Bakker *et al*. 2010). With 24 h operation, identifying localized problems with weeds or crop diseases, and then either applying local control, particularly for weed eradication, or feeding back to an information base for optimized large-scale interventions in the case of developing disease epidemics, may provide a more timely and controlled approach, often with less recourse to damaging vehicles.

Controlled traffic systems, which restrict the soil damage to accurately defined trackways in the field, have become much more practicable with the availability of global positioning satellites (GPS) and are another way in which machinery systems can be optimized, with production and environmental benefits (Tullberg, in press). Integrated approaches to machine-crop systems can be expected to follow from further innovation in these areas.

Real-time machine control for decreased pesticide (herbicide) input

The reduction in acceptability of some chemical interventions because of ecological impacts puts new pressures on intensive farming productivity and quality. For weed control, mechanical interventions are feasible but impractically slow without new control techniques. Real-time image analysis to control the tools has been demonstrated to be viable (Tillett *et al*. 2008). It draws on key strands in machine vision research, relating to stable discrimination under variable lighting conditions that are intrinsic to outdoor operations, pattern recognition and analysis of key contrasts between weed, crop, soil and debris. Operation at high speed and in wide bouts makes the technique match the requirements of high work rates for low cost production, and also meets the demands of organic systems where the weed pressures can be a critical factor in business sustainability (Bakker *et al*. 2010). The integration of sensing technologies with sophisticated machine control, linked to knowledge of spatial distribution of weed pressure, will contribute to more sustainable management systems.

It may not be feasible to replace herbicide use entirely with mechanical interventions, although the ability to operate under near full crop cover is greatly aided by precision navigation. However, the withdrawal of approvals for many chemicals suggests that a new paradigm may be upon many farming systems. These concepts may be relevant to insects and disease, although the mobility of these agents is much greater – early detection and finer-scale interventions require further research.

Systems modelling and management

Systems management based on efficient models of component processes and methods to optimize the performance of linked systems in relation to both economic and environmental goals will be of increasing importance (Wolfert *et al*. 2010). The principal challenges will be to demonstrate robust performance that gives practical advantages. These advantages include delivering enhanced quality of product to the consumer, and minimizing environmental impacts through an integrated approach to emissions control.

Data integration and data mining – information management systems for decision support and control

As well as the direct interpretation of sensor outputs to determine process control actions, there will also be advances in more general use of information about system performance to guide the management of complex systems. This can be expected to be particularly important in complex, interacting and continually changing systems – examples include optimization (minimization) of pesticide inputs, and food chain management from harvest through shipping to store and consumer. These approaches can also be a major contribution to traceability in the food chain (Kondo 2010). Increased use of widely available sensors can be expected to provide indicative information that can contribute to alarm monitoring or adjustment of setpoints. Much of the interpretation will draw on neural networks or similar optimization approaches that can handle large quantities of data and draw rapid conclusions based on learning approaches.

Models of farming systems, including life-cycle analysis, optimization and decision support

A major challenge is to identify and develop regulatory approaches that not only reflect national and global strategies for environmental protection but also can operate near-optimally in practice. Regulations are often blunt instruments, tailored for ease of use rather than maximal delivery of the required benefit. Life-cycle analysis (LCA) and other tools can provide holistic information on the impacts of production processes and the relative environmental damage associated with various products (Gnansounou *et al*. 2009; Meisterling *et al*. 2009). Farmer optimization in the face of regulatory constraints is generally going to be motivated by maximizing profit under the regulation. The result can be detrimental by steering farm systems into new areas that could be more damaging. Imposing regulatory ceilings on fertilizer or herbicide use can lead to major income reductions if accepted simplistically by the farmer, but crop management and rotation changes can have substantial unexpected environmental consequences. Annetts & Audsley (2002) used a linear programming whole-farm model to demonstrate how this might happen and the scope for more optimal management.

The concept of model-based assessment of the acceptability of farming systems in relation to environmental regulations still needs further study and development. Realistic yet parsimonious models are essential, yet will always be constrained in their validation.

Holistic management systems

The same approaches of modelling and process optimization can be applied to the management of inputs to crops. Excessive use of fertilizers and pesticides in intensive agricultural systems need to be avoided, yet optimal use is dependent on a wide range of factors, including soil type and past and future weather conditions. The development of modelling approaches that can integrate current knowledge of crop and weather with information on likely responses to fertilizers and pesticides have the potential to underpin near-optimal management regimes, oriented to minimizing environmental damage (Parsons *et al.* 2009). This is not a simple task. For example, although the optimal level of nitrogen fertilizer can be readily defined experimentally after the cropping season, by analysing outcomes, the ability to predict this optimum at the start of the season is highly problematic, and even in the spring at the time of the main dressings, the prediction accuracy is currently limited. However, the benefits are potentially considerable – losses of nitrates and possibly also of nitrous oxide are low when nitrogen levels are below the optimum for crop production, but increase rapidly when the optimum is exceeded. These complex tools will of course need effective means of communication to the decision maker, requiring effective approaches to decision support and the means to present the advice direct to the end user (Karmakar *et al.* 2007; Antonopoulou *et al.* 2009).

DISCUSSION AND CONCLUSIONS

The thesis underlying this review is that novel engineering methods and technologies, utilizing observations and models, can lead to greater control over key biological processes and by so doing enhance process efficiency and decrease damage to the environment.

The development of these methods depends on further advances in the underlying science, on the availability of facilitating technologies (both coming from the breadth of engineering and being developed specifically to match biological opportunities), and on increased sophistication and capability of integrating approaches in mathematics, data interpretation, communication and control. New approaches and technical advances will be particularly important to inject robustness and transferability into the methods and their practical realization.

The examples demonstrate that progress is being made, and that there are opportunities yet to be addressed or hurdles to be overcome. The scientific challenge associated with enhanced control of complex biological systems operating in the natural environment is considerable, and will require significant innovation in science and engineering. This paper emphasizes the importance of the interface between many disciplines, and this can be expected to be one of the most fruitful areas for science in the coming decades. Although depth and detail about specific aspects are limited, it is hoped that the importance of keeping biology, engineering and physics together has been demonstrated. Addressing the real-world complexity is an integral part of achieving robustly managed systems and providing the foundations for solutions to the global challenges of food production and environmental degradation that we now face.

REFERENCES

Annetts, J. E. & Audsley, E. (2002). Multiple objective linear programming for environmental farm planning. *Journal of the Operational Research Society* **53**, 933–943.

Antonopoulou, E., Karetsos, S. T., Maliappis, M. & Sideridis, A. B. (2009). Web and mobile technologies in a prototype DSS for major field crops. *Computers and Electronics in Agriculture* **70**, 292–301.

Bakker, T., van Asselt, K., Bontsema, J., Müller, J. & van Straten, G. (2010). Systematic design of an autonomous platform for robotic weeding. *Journal of Terramechanics* **47**, 63–73.

Dabbene, F., Gay, P. & Sacco, N. (2008). Optimisation of fresh-food supply chains in uncertain environments, Part I: Background and methodology. *Biosystems Engineering* **99**, 348–359.

Dawson, J. J. C. & Smith, P. (2007). Carbon losses from soil and its consequences for land-use management. *Science of the Total Environment* **382**, 165–190.

Gerbens-Leenes, P. W., Moll, H. C. & Schoot Uiterkamp, A. J. M. (2003). Design and development of a measuring method for environmental sustainability in food production systems. *Ecological Economics* **46**, 231–248.

Gnansounou, E., Dauriat, A., Villegas, J. & Panichelli, L. (2009). Life cycle assessment of biofuels: energy and greenhouse gas balances. *Bioresource Technology* **100**, 4919–4930.

Goel, P. K., Prasher, S. O., Landry, J. A., Patel, R. M., Bonnell, R. B., Viau, A. A. & Miller, J. R. (2003). Potential of airborne hyperspectral remote sensing to detect nitrogen deficiency and weed infestation in corn. *Computers and Electronics in Agriculture* **38**, 99–124.

Hatfield, J. L., Gitelson, A. A., Schepers, J. S. & Walthall, C. L. (2008). Application of spectral remote sensing for agronomic decisions. *Agronomy Journal* **100**, S117–S131.

Huang, Y., Lan, Y., Thomson, S. J., Fang, A., Hoffmann, W. C. & Lacey, R. E. (2010). Development of soft computing and applications in agricultural and biological engineering. *Computers and Electronics in Agriculture* **71**, 107–127.

Jansen, R. M. C., Hofstee, J. W., Wildt, J., Verstappen, F. W. A., Bouwmeester, H. J., Posthumus, M. A. & van Henten, E. J. (2009). Health monitoring of plants by their emitted volatiles: trichome damage and cell membrane damage are detectable at greenhouse scale. *Annals of Applied Biology* **154**, 441–452.

Karmakar, S., Laguë, C., Agnew, J. & Landry, H. (2007). Integrated decision support system (DSS) for manure management: a review and perspective. *Computers and Electronics in Agriculture* **57**, 190–201.

Kondo, N. (2010). Automation on fruit and vegetable grading system and food traceability. *Trends in Food Science and Technology* **21**, 145–152.

Lark, R. M. & Wheeler, H. C. (2003). A method to investigate within-field variation of the response of combinable crops to an input. *Agronomy Journal* **95**, 1093–1104.

Luong, J. H. T., Male, K. B. & Glennon, J. D. (2008). Biosensor technology: technology push versus market pull. *Biotechnology Advances* **26**, 492–500.

Meisterling, K., Samaras, C. & Schweizer, V. (2009). Decisions to reduce greenhouse gases from agriculture and product transport: LCA case study of organic and conventional wheat. *Journal of Cleaner Production* **17**, 222–230

Nayak, M., Kotian, A., Marathe, S. & Chakravortty, D. (2009). Detection of microorganisms using biosensors – a smarter way towards detection techniques. *Biosensors and Bioelectronics* **25**, 661–667.

Oliver, Y. M., Robertson, M. J. & Wong, M. T. F. (2010). Integrating farmer knowledge, precision agriculture tools, and crop simulation modelling to evaluate management options for poor-performing patches in cropping fields. *European Journal of Agronomy* **32**, 40–50.

Parsons, D. J., Benjamin, L. R., Clarke, J., Ginsburg, D., Mayes, A., Milne, A. E. & Wilkinson, D. J. (2009). Weed Manager – A model-based decision support system for weed management in arable crops. *Computers and Electronics in Agriculture* **65**, 155–167.

Rumpf, T., Mahlein, A.-K., Steiner, U., Oerke, E.-C., Dehne, H.-W. & Plümer, L. (2010). Early detection and classification of plant diseases with Support Vector Machines based on hyperspectral reflectance. *Computers and Electronics in Agriculture* **74**, 91–99.

Sinfield, J. V., Fagerman, D. & Colic, O. (2010). Evaluation of sensing technologies for on-the-go detection of macro-nutrients in cultivated soils. *Computers and Electronics in Agriculture* **70**, 1–18.

Slaughter, D. S., Giles, D. K. & Downey, D. (2008). Autonomous robotic weed control systems: a review. *Computers and Electronics in Agriculture* **61**, 63–78.

Spooner, A. D., Bessant, C., Turner, C., Knobloch, H. & Chambers, M. (2009). Evaluation of a combination of SIFT-MS and multivariate data analysis for the diagnosis of *Mycobacterium bovis* in wild badgers. *Analyst* **134**, 1922–1927.

Sylvester-Bradley, R. & Kindred, D. R. (2009). Analysing nitrogen responses of cereals to prioritize routes to the improvement of nitrogen use efficiency. *Journal of Experimental Botany* **60**, 1939–1951.

Thakur, M. & Hurburgh, C. R. (2009). Framework for implementing traceability system in the bulk grain supply chain. *Journal of Food Engineering* **95**, 617–626.

Tillett, N. D., Hague, T., Grundy, A. C. & Dedousis, A. P. (2008). Mechanical within-row weed control for transplanted crops using computer vision. *Biosystems Engineering* **99**, 171–178.

Tullberg, J. (in press). Tillage, traffic and sustainability – a challenge for ISTRO. *Soil and Tillage Research*, in press, doi:10.1016/j.still.2010.08.008.

Velasco-Garcia, M. & Mottram, T. T. (2003). Biosensor technology addressing agricultural problems. *Biosystems Engineering* **84**, 1–12.

Vouludimos, A. S., Patrikakis, C. Z., Sideridis, A. B., Ntafis, V. A. & Xylouri, E. M. (2010). A complete farm management system based on animal identification using RFID technology. *Computers and Electronics in Agriculture* **70**, 380–388.

Wang, N., Zhang, N. & Wang, M. (2006). Wireless sensors in agriculture and food industry – recent development and future perspective. *Computers and Electronics in Agriculture* **50**, 1–14.

Wolfert, J., Verdouw, C. N., Verloop, C. M. & Beulens, A. J. M. (2010). Organizing information integration in agri-food – a method based on a service-oriented architecture and living lab approach. *Computers and Electronics in Agriculture* **70**, 389–405.

Xu, Y. F., Velasco-Garcia, M. & Mottram, T. T. (2005). Quantitative analysis of the response of an electrochemical biosensor for progesterone in milk. *Biosensors and Bioelectronics* **20**, 2061–2070.

Zhang, N., Wang, M. & Wang, N. (2002). Precision agriculture – a worldwide overview. *Computers and Electronics in Agriculture* **36**, 113–132.