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Critical Review

Microsystems technology for remote monitoring and control in sustainable agricultural practices

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The future development of advanced sensor and microsystems technologies for use in agriculture is briefly discussed, within a general appraisal of the industrial requirements and the potential economic and ecological benefits to be derived from the employment of novel sensing systems in sustainable agricultural practices, such as precision farming. It is proposed that these technologies are potentially important monitoring tools for farmers and growers, and that a concerted programme of research and development is required to satisfy the future requirements of the agricultural industry.

Introduction

It is widely recognised that high productivity in current agricultural practice is often suboptimal in the use of resources and is accompanied by environmental degradation and reduction in natural biodiversity (Fig. 1). Typical consequences are contributions to soil acidification, mobilisation of potentially toxic elements and eutrophication of surface waters.[1] This is now unacceptable and national and European initiatives are underway to implement remedial actions through codes of good agricultural practice, cleaner technologies and environmental legislation. Lower input, sustainable and more efficient agricultural processes are now required.[2] This can be achieved, in part, by the optimal use of process inputs. Increasingly, farmers use management systems that promote more sustainable practices, such as precison farming, in which the custom application of agrochemicals and plant nutrients is a key instrument.

For optimal resource utilisation, with minimal waste and pollution effects, agricultural processes must be undertaken in a more systematic and integrated manner with accurate measures of input and output parameters. However, cost-effective, user-friendly, analytical tools have been unavailable to farmers and growers, and frequently the parameters which require measurement describe matrices (*e.g.* in soils, the rhizosphere, plant material, aerosols) which are difficult to monitor. One important and rapidly expanding technological development which may have implications for the management of agricultural practices is the advance in sensors, microengineering and microsystems technology. Future developments in these technologies could contribute, ultimately, to enhanced and sustainable productivity in agricultural practices, with significant reductions in environmental and financial costs.

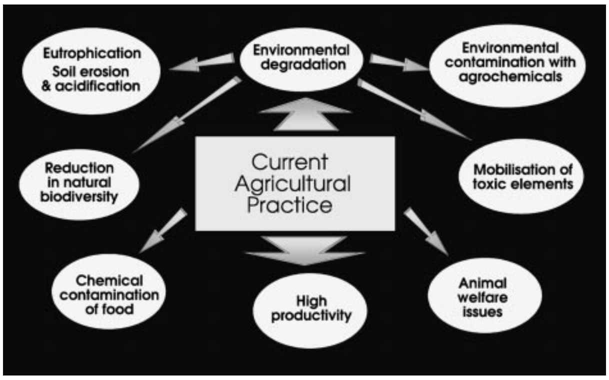

Fig. 1 Characteristics of some current agricultural practices.

In the context of the monitoring and control of agricultural processes, this paper provides a brief overview of: (i) management systems for sustainable agricultural practices; (ii) environmental, social and economic drivers for new technology implementation; (iii) advances and developments in instrumentation and technology for agriculture; and (iv) future trends in microsystems technology and agriculture.

Background

Agriculture accounts for over 1.8% of UK Gross Domestic Product (GDP) and 70% of UK land space utilisation.[3] These are typical statistics for a modern mixed economy. The impact of agriculture on the economy and ecological health of a country is therefore very important. The projected rate of growth of the global human population to 9 billion by the year 2050 will require an annual 75% increase in agricultural production.[4] In parallel to this requirement, societal attitudes towards the environment, public health, food quality and animal welfare will gradually place new demands on agriculture, and have already contributed to the general evolution of the concept of sustainability.[5,6] Since the 1987 World Commission on Environment and Development (WCED) Bruntland Report, "Our Common Future", the concept of sustainable development has been taken up in both political thinking and economic/environmental policies, and the agro-industries will be subject to these. In response to the subsequent Earth Summit at Rio de Janeiro in 1992, the Vth European Environment Action Programme (see Appendix 1) made clear demands on agriculture, with regard to nature conservation and natural biodiversity.[7] This has been recently reinforced by Agenda 2000 and moves to make the agricultural sector more competitive and quality conscious. Highly productive but sustainable agricultural practices are therefore a key future requirement, in particular, those that take a more systematic approach to the monitoring and control of agricultural processes.

Systems for monitoring and control in agriculture

There have been continual structural changes in agriculture since the time of the original subsistence farms. Today, modern market demands have produced agricultural change in the form of commercialisation, transformation and diversification.[8] This has resulted in the predominance of large, highly

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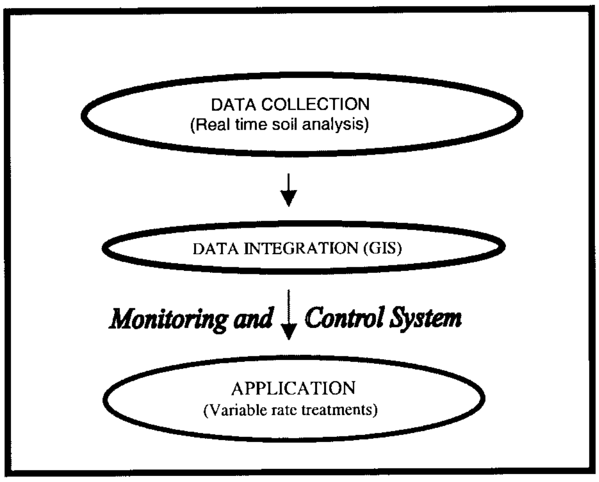

Fig. 2 Summary of the precision farming system.

specialised farms with increased contractual integration with agribusinesses. Consequently, mechanisation, fertilisation, seed hybridisation, chemicals and computers are typically used as management tools to enhance business performance, diversity and resilience, and to minimise the risks associated with variables, such as pests and weather. More recently, driven by the availability of complementary generic technologies, there has been a trend towards a reversal of uniform treatment management to the concept of site-specific management production. This takes advantage of high technology equipment to match crop inputs to yield, and to achieve "just in time" and "just enough" manufacturing management.[9] Spatial management is not a new idea, because farmers all over the world have traditionally tried to match cropping practices to soil type, climate and other landscape characteristics. Today, however, environmental incentives, economics and advancing technology make it more beneficial and feasible. Despite these advances, significant problems still exist for the modern farm.[10] Market pressures and shifting consumer preferences call for more specialised identity-preserved products. Diminishing returns for produce require more stringent controls of inputs. In addition, social movements, legislation and environmental concerns highlight the need for new management systems that can address these demands.

Precision farming

Precision farming is a management system that promotes environmental monitoring and control in agriculture. This approach was first adopted in the USA in the mid-1980s,[11] but has now spread to Europe and other parts of the world. The system is a technology- and information-based management system that promotes controlled agricultural practices. It aims to: (i) understand the spatial distribution of factors affecting the growth of the crop; (ii) manage this spatial variability by applying a variable rate treatment of agrochemicals and plant nutrients within a field according to site conditions; and (iii) maximise profits and minimise environmental impacts.

Such techniques are currently used for nutrient application, but the same principles and similar technologies are also applicable to the use of herbicides, pesticides and fungicides. The technologies available to farmers for precision farming include: (i) global positioning systems (GPS); (ii) field sensors; (iii) variable rate applicators (VRT) for nutrients and agrochemicals; (iv) yield monitors for harvesting; (v) computer systems in the cab; (vi) user-friendly software for data collection storage and feedback control systems; (vii) remote sensing; (viii) soil sampling; and (ix) geographic information systems (GIS).

It is possible to adopt the above technologies for use in site-specific applications at varying levels of specialisation and sophistication according to the needs and capacities of the individual producer. In its most extensive form, there will be precise management of every step in the management programme. By contrast, the simpler interpretation will require manual application and non-automated implementation.[12]The former is, in the main, more suitable for the larger highly capitalised farms. It is therefore expected that agrochemical industries and suppliers will make the investment in many of the high technology packages to offer them as custom services.[10]

A summary of the system is shown in Fig. 2. A central database (GIS) is used to control and analyse input and output data functions. Inputs include raw data on the physical, chemical and biological nature of the soil and the factors that affect plant growth. Data are collected using a wide range of tools, including remote sensing, field sensors, topography, soil type, drainage, rainfall, yield sensors and soil analysis. Outputs take the form of yield/nutrient maps and managerial decisions for variable rate treatments of plant nutrients to crops.

The critical missing technologies to form effective monitoring and control systems are appropriate diagnostic tools for "on-the-go" analysis of key parameters, such as soil pH, nitrates or indicators of plant health. Rugged, low power, high precision tools need to be developed for this purpose. Traditional methods involve manual data collection, but this is limited by time and cost and is not suitable for precision farming practices. There is an immediate need for "real time" automatic sensors to produce data that can be readily integrated into the decision-making components of a precision farming system. The development of appropriate sensors is a major hurdle that needs to be overcome, and a concerted programme of research and development is required to attain this objective.[13]

Environmental, economic and social drivers towards technology implementation

The route to sustainable agricultural production will move away from current agricultural practices within the European Union (EU),[14] and towards applied agroecology and fewer harmful agrochemical inputs.[15] There is an ongoing need for higher production, greater efficiency and more economic and sustainable agricultural practices and management tools, such as precision farming. Many of these technologies aspire to supply the missing link in the management of agroecosystems, where there is little or no control of input parameters according to actual requirements. In the UK, the government's wide-ranging Technology Foresight Programme on agriculture and environment has concluded that, in future, the optimal implementation of sustainable farming practices will be enhanced by specific developments in engineering, particularly instrumentation systems for monitoring and control.[3] The following factors are likely to govern the changes in agricultural management systems and technology implementation: (i) research and development of new technologies; (ii) Agenda 2000 and the development of the World Trade Organisation (WTO); (iii) devolution of government and political pressures; (iv) enlargement of the EU and the expansion of the developing countries; (v) increase in grain and protein demands; (vi) social/political unrest; (vii) outbreaks of pests and diseases; (viii) sustainable agriculture; (ix) food safety and quality; (x) increased competition; and (xi) farm and global economies.

Environmental drivers

As the environmental consequences of modern farming methods come under increased public scrutiny, concern is being voiced over long-term damaging effects on the ecosystem and human health. In an effort to restore public confidence, governments, at both national and international level, have introduced incentives, directives and legislative control. These have attempted to ensure that farmers optimise their use of resources, operate efficiently and minimise waste and pollution effects. Much attention has been focused on the principle of "sustainable agricultural development". This encourages farmers to deliver desirable, quality products in a manner which is environmentally and socially acceptable, and economically efficient.[16]

Intensively managed farms growing high value crops have been targeted as having a number of adverse environmental effects, such as water pollution, atmospheric pollution and soil degradation/erosion.

Water pollution. High fertiliser and pesticide application rates can result in the leaching of excess chemicals into ground water or streams, possibly contaminating drinking water. The associated risk to human health of these chemicals, particularly nitrates, has led to tighter controls, including the EU Nitrates Directive (91/676/EEC) that imposes limits on the nitrate levels allowed in drinking water ($50\,\mathrm{mg\,l^{-1}}$ for nitrate). In the UK, Nitrate Sensitive Areas (NSA) have been established by the Ministry of Agriculture, Food and Fisheries (MAFF), with mandatory prohibitions on the use of fertiliser in these zones (Water Resources Act 1991). In Sweden, the government has imposed a tax on fertiliser and pesticides,[17] and other countries may follow suit.

Atmospheric effects. Agribusiness contributes to air pollution and global warming with emissions of carbon dioxide, nitrous oxide and methane. This issue is high on the global agenda following the recent round of negotiations at the "Climate Change Convention" in Kyoto. Following applications of urea, 15–20% of nitrogen can be lost to the atmosphere as nitrous oxide. This has a potential global warming effect 300 times greater than that of carbon dioxide.[18] Livestock, silos, mechanisation and denitrification in soil are the principal sources of methane and nitrous oxide emissions.

Soil degradation/erosion. Conventional tillage systems leave the soil bare, smooth and susceptible to wind and water erosion. Topsoil contains most of the soil's nutrients and organic matter. Soil erosion can remove these nutrients, lower the water holding capacity of the soil, alter pH values and reduce crop yield. The addition of fertiliser can amend the soil's nutrient status, but will do little to improve organic matter levels or root growth. Nutrient losses are inevitable as crops are harvested. Low yielding crops often extract nutrients from the soil at a rate three to four times faster than they are replaced. In some parts of Africa, for example, the net nutrient loss from the soil is estimated to be 10 million tonnes per year.[18]

In general, the effects of these changes in farming have been a move away from the notion of farmers as the custodians of the environment towards more systematic methods of environmental monitoring. At first, farmers were enticed into environmentally good practices by the offer of incentives not to undertake potentially harmful activities. Gradually, this approach has changed to rewarding farmers for undertaking environmentally worthy practices, *i.e.* the positive management agreement. More recently, the Common Agricultural Policy (CAP) Reform Agreement (Agenda 2000) requires member states to implement, within horizontal measures, payment of certain European funds on condition of specific environmental conditions.[19] It is very much in the interests of the agricultural community, therefore, to make use of all available means to reduce their environmental impact. What is significant now is the use of new technology to achieve these goals. For example, if India had to produce its current crop yield of wheat using 1970's technology, an additional 40 million hectares would be required.[18]

Legislative drivers

Legislation for environmental protection in Europe has evolved piecemeal with *ad hoc* responses to crises. The most important aspect affecting the farming community is water quality, both surface and ground water. Non-point source pollution is now, probably, the major source of aquatic pollution and is a target area for improvement. It is this area, in particular, where the farmer is likely to benefit from technological advances in monitoring chemical parameters. The Single European Act was a starting point for environmental issues as part of the European Common Policy. The Montreal Protocol and the Vienna Convention formalised further commitment, but the most significant step towards environmental awareness was taken at the Rio de Janeiro Summit in 1992, which committed governments to the development of "sustainable economic policies" that take into account environmental effects.[20] The need for environmental assessment is likely to have an impact on many areas of farming and may force a more scientific approach. In the future, it is likely that farmers will be expected to demonstrate that businesses are conducted using a system of environmental management, such as that recently introduced under the European Eco-Management and Audit Regulation (EC/93/1836).

New laws governing environmental legislation now follow three main guiding principles as outlined below.

1. The precautionary principle. The farmer must take every precaution possible to prevent environmental degradation, taking into account available technology and the cost needed to attain that improvement.[21]

2. The subsidiary principle. This delegates legislative implementation to national level in the form of directives, such as The Nitrates Directive (91/676/EEC), The Drinking Water Directive (80/778/EEC), Agri-environmental Regulation (EC/2078/92), The Directive on Maximum Levels of Pesticide Residues (94/29/EEC) and The Environmental Assessment Directive (85/337/EEC) (Appendix 2).

3. The polluter pays principle. This principle was first formulated by the Organisation for Economic Co-operation and Development (OECD) in the early 1970s.[22] In 1975, the European Community defined this principle as the basis for its environmental policy. However, lack of precise legislation has made it difficult to apply in practice. Nevertheless, it is a part of many government policies and has received increased focus recently, for example the possible threat of a nitrogen and pesticide tax.

Society will benefit ecologically in many ways from technical advances in monitoring techniques, a cleaner environment, safer food and water supplies and more careful use of resources. Site-specific management of inputs, in terms of more accurate and precise application of chemicals and fertiliser to match plant nutrient needs, will reduce the danger of leaching and run off into ground and surface water. The ability to identify areas of compaction and implement appropriate remedial actions will reduce other environmental problems. Society, through legislation, could force the adoption of site-specific technology, or it could offer inducements that would improve profitability. The following extensions of the above principles have been recommended: (i) mandatory environmental audits; (ii) the payment of subsidies only on condition of the use of sound agricultural practice; (iii) fertiliser and pesticide taxes; (iv) higher penalty for pollution; (v) compulsory adoption of the use of the best technology available rule; and (vi) technology availability: this has been assisted by the US Environmental Protection Agency's Environmental Technology Initiative-A grant program that seeks to convert defence technologies for environmental applications. These, should they become a reality, could be the main driving forces towards the adoption of precision farming techniques.

Food safety and production drivers

The ability to closely regulate crop inputs and maintain detailed production records supports the interests of many parties in the agricultural production line. Rapidly changing consumer preferences towards identified products requires increased monitoring and measurement of inputs for quality control accounting. Following the introduction of Sainsbury's Integrated Crop Management System (ICMS) policy in 1991, there are now crop production protocols and auditing for individual crops.[23] This trend has accelerated with the recent controversy over genetically modified foods. The introduction of new technology for monitoring and control, and the adoption of precision management systems, will permit manufacturers to extend quality control measures. It will enable the tracking of inputs to produce, from the point of manufacture, right through the production/distribution chain, to the end user (life cycle accounting). This will reduce concerns over product liability and the risk of potential food contamination, consequently increasing consumer confidence and food safety. At the farm level, precision farming is a production and planning tool supporting better investment decisions. Surplus production, competitive markets, industrially manufactured substitutes and alternative raw materials have put pressure on farmers to enhance productivity. Precision farming may offer a competitive advantage in production efficiency.[8,10,24]

Measurement systems and miniaturisation

Sensing requirements

For the development of optimised, but sustainable, agricultural systems, farmers require a broad range of analytical and monitoring tools so as to enable the implementation of cleaner process control (*e.g.* for soil and plant analysis).[25]

These sensing requirements include, but are not limited to, the following broad categories: (i) nutrient status of soils and hydroponic systems in glass houses (N, P, S, Ca, moisture, pH, soil organic matter); (ii) stress detection in growing plants; (iii) pesticide resistance profile of insect populations for integrated pest management; (iv) verification of organic status growing conditions; (v) suitability of silage liquor and slurries for field application; (vi) forecasting of pest and pathogen outbreaks; (vii) airborne dust, ammonia and humidity in livestock buildings; (viii) analysis of soil-borne pests and pathogens; (ix) pesticide persistence in soils and on crops; and (x) specific identification of insect pest variants.

Towards miniaturisation

The miniaturisation of traditional instrumentation systems enabled by recent advances in microelectromechanical systems (MEMS) and other microtechnologies (microsensor and microactuator), and consolidated by the emergence of microsystems technology (MST),[26–28] may facilitate the move away from the laboratory setting to remote, distributed and on-site locations. It is expected that complex analytical instrumentation that is currently bound to a laboratory will become commercially available as pocket-sized systems, which can be used in remote field situations.[29] A good example of this shift in technology is the "laboratory-on-a-chip" (Fig. 3).[30] Such chemical chips hold miniature equipment for chemical and biochemical analysis or synthesis.

MST is progressively condensing mechanical, electrical, optical and chemical systems into small, self-contained instruments. Their future application will resolve some of the difficult volume, power and maintenance constraints currently imposed on the design of analytical instrumentation for chemical and biological parameters. The scope for agriculture and environmental monitoring is considerable,[31] and the specific availability of miniaturised analytical instrumentation offers the prospect of tools for the implementation of cleaner agricultural processes for farmers and growers.

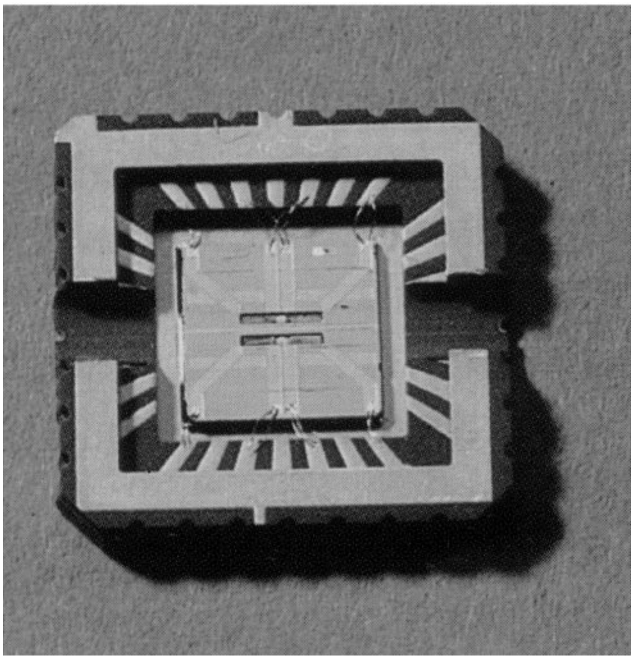

Fig. 3 "Laboratory-on-a-chip" technology: the future of chemistry is getting smaller. Reproduced from ref. 30 with permission.

Field sensors

The development of "real time" soil property sensors for monitoring and control systems has been an important goal for several years. Rapid soil sampling, yield sensors and data interpretation are already in use and further developments are likely.[32] This has resulted in automated, soil nutrient mapping systems, using soil analysis, GPS and GIS. A number of tractor-mounted sensing systems for "on-the-go" soil analysis have been designed and tested. In 1991, Adsett and Zoerb[33] designed an electrochemical nitrate monitoring system that operated at 3 km h^{-1}, sampled every 20 m and had a processing time of 24 s. In 1995, Birrell[34] developed a flow injection analysis (FIA), multi-ion-selective field-effect transistor (ISFET) sensor for measuring soil nitrate concentration, with an analysis time of 1.25 s for manually extracted soil samples (although the results obtained using an automatic extraction procedure were not so successful). More recently, in 1998, Ferreira *et al.*[35] reviewed the application of FIA for soil analysis and Rossel and MacBratney[36] evaluated potentiometric pH sensors for "on-the-go" field measurements. A "real time", tractor-mounted crop nitrate sensor, developed by HydroAgri, that remotely measures the chlorophyll content of the plant, has shown good performance in field trials and should soon be available commercially.[37] However, many of these systems are new to the market. The accuracy and reliability are yet to be established.[32] Most existing methods for "on-the-go" measurements of soil nutrients are slow, labour intensive and ineffective.

Currently, potentiometric [particularly ISFET (Fig. 4) and ion-selective electrodes (ISEs)], amperometric and optochemical methods are being extensively investigated for the production of ion sensors for nitrate, potassium, pH and ammonium.[38–44] These devices represent miniaturised versions of conventional laboratory ISE produced using microelectronic mass fabrication techniques.

One technique that is readily transferable from the laboratory to remote settings is optochemical analysis (Fig. 5). Sensors based on optical fibres, planar optical waveguides, metallised prisms and diffraction gratings have been developed for monitoring dissolved oxygen, carbon dioxide, pH and ammonia.[45] A prototype fibre-optical chemical sensor (FOCS) was designed by Stanley *et al.*[46] to detect nitrate levels in river water. A number of portable systems (PetroSense, Aquasense and

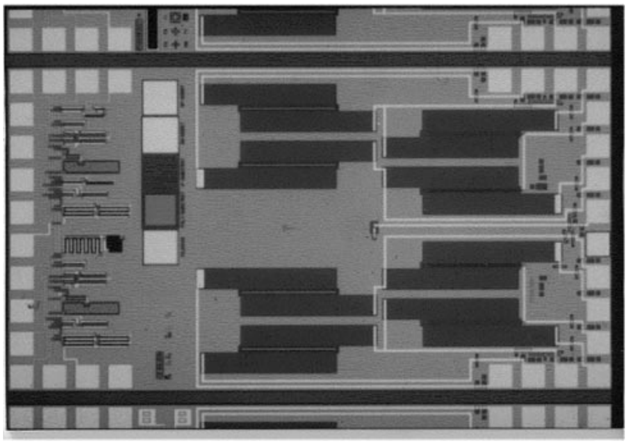

Fig. 4 Example of an ion-selective field-effect transistor (ISFET). This solid state device (4 × 7 mm footprint) is sensitive to pH. (Courtesy of Dr Peter Woias, Fraunhofer Institute of Semiconductor Technology, Munich.)

Aersense) are commercially available for the *in situ* monitoring of hydrocarbons, carbon dioxide, oxygen and ammonia.[47] However, these devices are costly and cumbersome. The future success of these systems relies on the development and production of miniature, low cost and durable sensors.

This technology lends itself to miniaturisation. Integrated chip-based FOCS have been developed using MST that incorporate all the basic elements of optical sensors: light source [light-emitting diode (LED)], waveguide and detector (photodiode). The limiting factor in these devices is the availability of wide wavelength range, chip-compatible LEDs.[47] The major advantages of these sensors are that no sample pretreatment is needed, they do not suffer from electrical disturbances or drift and they offer the possibility of internal calibration without the need for a reference element. However, the dynamic operating range of the sensor may be limited (optical pH sensors can only detect one or two units around the pK_a value of the sensor reagent[48]) and the lifetime is restricted by the stability of the detecting reagent.

The much-researched field of chemical sensors sustains many unresolved problems concerning sensor specificity, stability, durability and functional dependence on additional environmental parameters when such devices are deployed in field conditions. Nevertheless, a higher degree of specificity, stability and multiparameter detection has been achieved using arrays of sensors and chemometrics.[49] Comprehensive reviews of the advances in sensor technologies can be found in Schueller,[50] Hummel *et al.*[51] and Rossel and McBratney.[52] Alternative soil tools, such as soil acoustics and ground penetrating radar, have been used by others to measure variability in soil texture, while electromagnetic induction, conductivity, capacitance and time domain reflectometry techniques have been used to measure soil moisture.[53,54] Soil organic matter sensors based on light reflectance have been relatively successful.

From microsensors to microanalysers

Until now, the development of miniaturised sensors based upon amperometric, potentiometric and optical mechanisms has failed to deliver the required technology in many respects for anything but short-duration usage. Additional subsystems for sensor calibration, storage, sample preparation and delivery are needed, requiring the complication of ancillary components for fluid control, such as miniaturised filters, mixer valves or pumps (Fig. 6).[55]

Much research continues with the objective of providing reliable miniaturised systems with integrated fluid control. Micropumps [Institute for Microelectronics, Mainz (IMM)], valves [Twente Microproducts (TMP)], mixers (Microparts) and microsieve filters (Aquamarijn) are now commercially available, and the key technical challenge in this development is for system integrators and packaging solutions which have whole wafer,[57] modular two-dimensional (2-D)[58,59] and modular 3-D[60,61] schemes (Fig. 7).

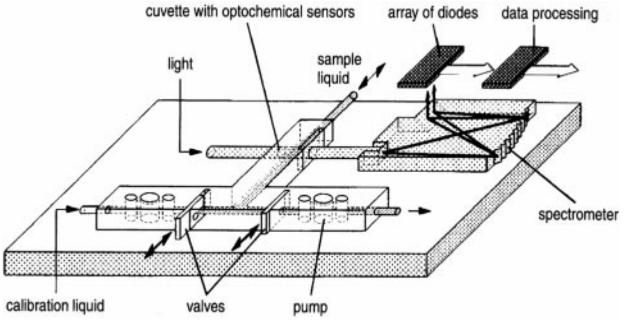

Fig. 5 Concept of an optochemical analysis system on a chip. Reproduced from ref. 31 with permission.

Parallel developments in the techniques used in molecular biology,[62] such as chromatography separation science and genetic analysis using gene probes,[63–66] can now be achieved on planar chip-based platforms (Fig. 8),[67] using an increasingly diverse set of techniques for micromachining substrate matrices, including silicon,[68] glass[69] and polymers.[70] These systems, which also incorporate functionalities for sample preparation (*e.g.* clean-up, preconcentration), injection, separation and detection,[71] have been targeted principally at the pharmaceutical and medical industries,[72,73] but many of the technologies provide generic solutions that are equally applicable to applications in agriculture and environmental monitoring.

The advantage of translating chromatographic and genomic techniques onto chips is that a far greater bandwidth of chemical information can be generated.[74] However, this technology exploits, in the main, the use of capillary electrochromatography (CEC) and capillary electrophoresis (CE), which utilise electro-osmotic fluid control.[75] These methods are not widely employed in the pharmaceutical industry, which is still heavily dependent upon the use of more traditional techniques, such as pressure-driven, high performance liquid chromatography (HPLC). However, chip-based products using CEC and other relatively novel techniques may receive a more immediate market acceptance in agriculture, where the need to displace an existing technology is a lesser problem.[76] Microanalytical chromatographic and genomic systems have generally been developed as card-reader instruments where a small disposable microfluidic cassette is "read" by a much larger instrument. The large size of the reader still requires considerable miniaturisation, but a number of hand-held prototype instruments have been developed especially for applications in the military.[77,78]

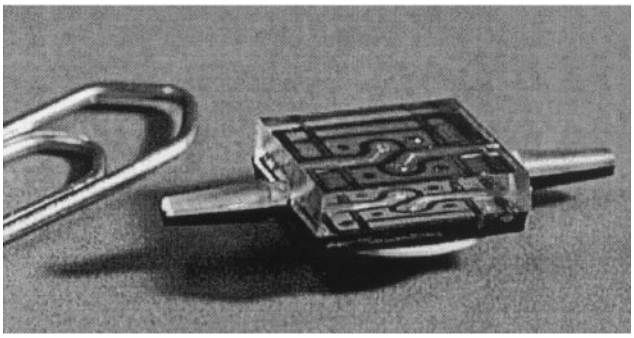

Fig. 6 Commercially available micropump for Institute for Microelectronics, Mainz (IMM). Reproduced from ref. 56 with permission.

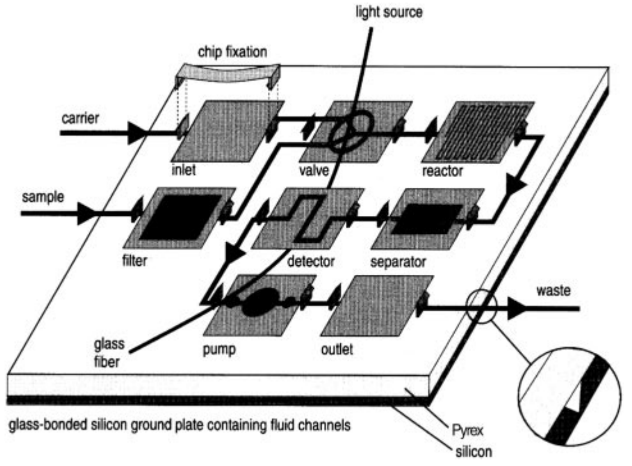

Fig. 7 Modular chemical analysis system. Reproduced from ref. 31 with permission.

Fingerprinting systems

Whilst specific sensors, sensor arrays and more comprehensive spectral analytical techniques hold the potential to generate a wealth of quantitative and qualitative specific chemical data on complex chemical matrices, there are also uses for semi-quantitative screening tools which may mimic certain biological sensing systems. For gas phase matrices, such as carbon monoxide, methane, hydrogen sulfide and nitrous oxides, this has been largely accomplished with the development of electronic "nose" technologies.[49,79] These usually rely upon the use of an array of similar, non-specific sensors with overlapping sensitivity profiles and pattern recognition techniques for analysis.[80] More recently, researchers in California have successfully developed a "nano" nose to detect the toxic gases, nitrogen dioxide and ammonia, using carbon nanotubules (cylindrical buckyballs) as the sensing element.[81] These nanotubules are small enough to be used in "laboratory-on-a-chip" technology, but have the drawback of slow response times.

A similar approach for the development of an electronic "tongue" to function in liquid matrices has also received recent attention.[82] Taste sensors for milk,[83] amino acids and mineral water[84] have been demonstrated. In most of these studies, the functional operation of the systems proposed relied upon the pattern recognition of electrode potentials from arrays of electrodes coated with lipid membranes. However, these delicate structures (some using Langmuir–Blodgett films) are not suitably durable for most industrial applications. One exception to this was the use of different chalcogenide glass-forming systems.[85] Such sensors could find numerous applications in the agricultural sector for the detection of animal health, pesticides and environmental impact.[31] For example, it has been proposed by Martin *et al.*[86] that such devices may be employed for the detection of ketosis in dairy cattle.

Monitoring tags

In September 1998, Britain saw the introduction of a new cattle-tracing system (CTS) by the British Cattle Movement Service (BCMS in MAFF). This was followed by an EU requirement for all member states to have a computerised tracing system by the end of 1999.[87] Coated implantable microchips have proved to be a very effective method of electronic tagging in animals. These microchips can be recognised using a radiofrequency identification (RFID) tag linked to a nearby radiofrequency antenna *via* a bar code and optical character recognition system. Government trials of these devices are currently underway to allow the introduction of a standardised system in the near future.[88] Similar systems, but using different microsensors, are likely to be developed for the measurement of various physical and chemical parameters inside the animal. For example, thermosensors and pressure sensors can be used to give an indication of the health of the animal. Hormone levels, such as progesterone, oestrogen and prostaglandin, could be monitored to detect ovulation, condition of pregnancy or illegal hormones in calves for slaughter.[31]

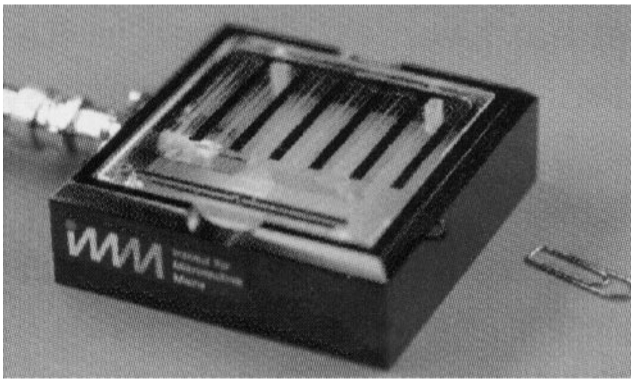

Fig. 8 Channel electrophoresis chip for DNA separation (IMM).

Satellite remote sensing

At present, satellite and ground-based remote sensing for crop management is a target of much research. Remote sensing was introduced to agriculture in the 1960s.[89] More recently, a number of on-going projects, largely funded by the European Commission, government services and agrochemical companies, have advanced the development of satellite and ground visual image systems and prepared the way for the launch of commercial satellites.[90] These include the HGCA (Home Grown Cereals Authority) Project, the Spartan Project and the XSTAR Project, which is due to launch its first satellite in 2002. Developments in synthetic aperture radar (SAR), although a few years behind the optical imaging systems, could provide wider applications. Cost and image capture restrictions are limiting factors and, as yet, few farmers can justify the adoption of this technology. However, competition and value added products, as part of commercial packages linked to information services, will make remote sensing more attractive in the future.[91] Possible products and services include data on: (i) soil organic matter; (ii) soil moisture; (iii) plant nitrogen levels; (iv) weed mapping; (v) crop condition; (vi) crop ripeness; and (vii) crop height.

Miniaturisation through the use of MST will facilitate smaller so-called nanosatellites,[92] which may comprise stacks of wafers resulting in platforms measuring 4 in (approximately 10 cm) in diameter and weighing 275 g.[93] MST will enable miniaturisation of both optical instrumentation systems for imaging and data processing as well as microfluidic based propulsion and positioning systems for operation in the space environment. This de-materialisation should facilitate the use of smaller and less expensive launch vehicles over the next decade.

Smart plants

Stress in growing plants frequently results in an increase of intracellular calcium concentration [Ca^{2+}], which can be indicative of specific physiological problems related to plant health. In 1991, Knight *et al.*[94] reported the development of a new technology for measuring [Ca^{2+}], based on the transformation of living plants with the cDNA for apoaequorin, a soluble, calcium-sensitive luminescent protein from a jellyfish, *Aequorea*, which glows when stressed. When combined with a small molecular weight luminophore, coelenterazine, luminous plants were generated whose luminescence directly reported [Ca^{2+}]. Such plants immediately luminesce in response to fungal elicitors, wounding and various stress treatments, permitting the potential specific and rapid diagnosis of particularly harmful agents. In that seminal 1991 paper, the inventors suggested that luminous crop plants could enable the farmer to accurately pinpoint sources of disease and pests and apply accurate, effective and minimal doses for control. Visible light emission from stressed plants opens up several opportunities for remote monitoring. For instance, as an early warning diagnostic system of crop stressors, satellite remote monitoring may be considered, if canopy reflectance is altered by interference phenomena in transgenic plants. Alternatively, individual sentinel indicator plants may be tagged or monitored with photoimagers and stress-related data integrated within "expert" monitoring and control systems. During remedial treatment, imaging systems on spatially variable spray applicators may allow the detection and identification (stressors) of stressed plants to localise and optimise spray application. Developments in MST, particularly in the fields of micro-optics[95] and low light level imaging systems,[96] hold the potential to supply the vehicle-mounted (*e.g.* tractor, aircraft) monitoring systems that will be required, once the safety issues of genetic transformation and the release of genetically modified crops have been resolved.

Conclusions

Currently, the key environmental problems arising from agricultural practice are diffuse pollution, particularly from pesticides and nitrates, and point sources such as slurries from dairy farms. To minimise and ultimately eliminate these and other problems, a diversity of new agricultural practices and technologies will assist in the development of clean technologies in agriculture. There is an urgent need for new monitoring instrumentation technologies, for use by farmers as a vital tool in their day-to-day activity as process controllers. Advances in sensor and microsystem technologies will become increasingly important, firstly as research tools and then as commercially available devices, over the next decade. To foster such developments, the effective integration of agricultural, ecological, socio-economic, legislative, technical, manufacturing and marketing inputs is required. Amongst the problems for the application of MST in agriculture may be the predominantly niche nature of most market opportunities (which characterise most environmental technologies), combined with the problems of technology uptake by companies with a hierarchical management structure.

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Appendix

Appendix 1

The Vth Environment Action Programme

The Vth Environment Action Programme (CEC, 1992) lays down three main objectives for achieving sustainability in farming: (i) maintenance of natural processes; (ii) decrease in input of chemicals; and (iii) management of the rural environment for biodiversity.

Target areas for particular attention for reaching these objectives include: (i) stabilising nitrate content in ground water; (ii) reducing nitrate content of surface waters to prevent eutrophication; (iii) maintaining appropriate organic levels in soils; (iv) significantly reducing the use of pesticides, especially in areas of nature conservation value; and (v) bringing 15% of agricultural land under management agreements to protect biodiversity.

Some measures to achieve these targets have already been introduced; others are in the pipeline or await further development. The Action Programme makes particular reference to: (i) strict application of the Nitrates Directive; (ii) emission standards for new livestock units and silos; (iii) reduction programme for use of phosphates; (iv) coupling of payments to environmental initiatives; (v) registration and control of sale and manufacture of pesticides; (vi) promotion of integrated control systems and bio-agriculture; (vii) review of irrigation licences; and (viii) protection of endangered species.

Appendix 2

Directive or regulation	**Implications and developments**
Agri-environment Regulation (EC/2078/92)	Positive management schemes—monitoring
Dangerous Substances in Water Directive (76/464/EEC)	Limit values set in daughter directives
Surface Waters Directive (75/440/EEC)	Draft directive on ecological quality of surface waters published in 1994
Drinking Water Directive (80/778/EEC)	Standards raised with technological improvements in detection
Groundwater Directive (80/68/EEC)	Council Resolution for amendment passed in 1994
Nitrates Directive (91/676/EEC)	Voluntary nitrate-sensitive areas to be replaced with nitrate-sensitive zones
Waste Framework Directive (75/442/EEC)	Amended by Waste Directive (91/156/EEC)
Hazardous Waste Directive (91/689/EEC)	Hazardous Waste List includes agrochemical wastes (Council Decision 94/904/EEC)
Directives on Maximum Levels of pesticide Residues (94/29/EEC and 94/30/EEC)	New regulations introduced in UK in 1995
Environmental Assessment Directive (85/337/EEC)	Currently under review

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