Securing soils for sustainable agriculture

A science-led strategy

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About this publication

'Optimising Soil Chemistry for Agriculture and Resource Efficiency (OSCAR)' was a workshop held at the Royal Society of Chemistry, Burlington House, London on 28th and 29th November 2011. It brought together leading academics, industrialists and policymakers to discuss future problems in the area of soil sustainability.

This report is a record of the workshop discussions. The RSC would like to thank the joint organisers of the event, the University of Sheffield, the Natural Environment Research Council and the Environmental Sustainability Knowledge Transfer Network for making this event possible.

The Royal Society of Chemistry

The Royal Society of Chemistry is the leading society and professional body for chemical scientists. We are committed to ensuring that an enthusiastic, innovative and thriving scientific community is in place to face the future.

The RSC has a global membership of 48,000 and is actively involved in the spheres of education, qualifications and professional conduct. We run conferences and meetings for chemical scientists, industrialists and policymakers at both national and local levels.

We are a major publisher of scientific books and journals, the majority of which are held in the RSC Library and Information Centre. In all our work, the RSC is objective and impartial, and we are recognised throughout the world as an authoritative voice for chemistry and chemists.

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About the ESKTN

The Environmental Sustainability Knowledge Transfer Network is sponsored by the Technology Strategy Board (TSB), the government's leading body for business-led innovation. Our primary role is to catalyse development and uptake of innovative technology-based products and services for future markets, accelerating the transition to a low carbon, resource and energy efficient economy.

We connect businesses, universities, other research organisations & government agencies, driving the flow of people, knowledge and experience between businesses and the science base. We also provide a forum for a coherent business voice to inform government of its technology needs and about issues such as regulation which are enhancing or inhibiting innovation in the UK.

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About the NERC biological weathering consortium

This research consortium, funded by NERC, is composed of research teams from the Universities of Sheffield, Leeds and Bristol. Their research examines the soil processes responsible for the biological transfer of mineral nutrients to plants. The project focuses on the role of symbiotic soil fungi that utilise photosynthetic energy captured by the host plant, to grow, pervade soil and extract mineral nutrients that supply the host. The OSCAR workshop has been the main Knowledge Exchange (KE) mechanism for the project teams to engage with research users in industry and government, and with other research experts, tackling nutrient utilisation and resource efficiency in agriculture and related applications.

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Knowledge Transfer Network Environmental Sustainability

Biological Weathering *in Earth Systems*

Executive summary

Food security is one of the great global challenges of the 21st century. Soils, and their continuing ability to support the sustainable intensification of agriculture, will play a central and critical role in delivering food security. The pressure on soils is urgent and growing, but the complexity of soils creates significant challenges to establishing the robust science base needed to support key decisions on their future management. Since soils and food supplies are global issues, gaining and maintaining international consensus on soil management poses further scientific and diplomatic challenges.

The UK has a strong international reputation in both soil and environmental change science and an unrivalled catalogue of soils data. As an important R&D and production location for major agrochemical and agricultural technology multinationals, with a strong base of soil science professionals, the UK should be well-placed to lead international strategy on securing soils and food sustainability.

Despite this, effective knowledge exchange and uptake of science-led innovation is limited in the UK by the high costs of developing agrochemical products and technologies in a context of regulation which is necessarily cautious but in some cases appears unnecessarily prohibitive. There can be negative interactions between policy drivers for innovation and industry and those for environment and health, with potentially high-value university- and SME- led R&D opportunities often relinquished by an inability to enter and survive in this marketplace.

Education of a new generation of scientists and professionals who can integrate plant, soil, water and land management is critical. To foster innovation, alongside producing graduates with specialist knowledge, higher education needs to ensure such specialists are capable of delivering interdisciplinary solutions. There is a strong developing framework for more effective research-industry engagement within the UK but this must be funded and maintained to secure the next generation of soils/food research through 2020 and beyond.

Priority research opportunities

Meeting attendees identified four future projects that offer the potential to provide solutions to support improved soil management in the future:

1. Creation of closed loop systems for recovery of major nutrients, water and micronutrients from low-grade farm and food wastes to reduce dependence on primary stocks and global markets;
2. Development and application of high sensitivity, high resolution biosignalling and sensor technologies to support precision agriculture and more sophisticated regulatory testing;
3. Detailed and robust understanding of molecular-scale biogeochemical processes associated with phosphorus uptake at and around plant roots, to stimulate the development of target-specific, 'smart' agrochemical agents;
4. Integrated models of plant-soil-water interactions and development of methodologies to upscale from laboratory to field and landscape to inform soil management policies, climate change mitigation and adaptation to environmental change.

Strategic objectives for soil science and agriculture

1. Establish a recognised and supported knowledge supply chain for sustainable agriculture and soil technology, connecting highly innovative R&D and SMEs with regulators, legislators and multinationals. This should be directed by the Knowledge Transfer Networks and learned societies;
2. The Royal Society of Chemistry should work in partnership with other key professional institutions and scientists to promote soil sustainability and align soil science priorities with wider public environmental concerns;
3. RCUK and other research funders should expand interdisciplinary approaches to problems in soil conservation and sustainable agriculture by supporting engagement with economists and social scientists in identifying the key environmental datasets that underpin the valuation and budgeting of soil stocks and ecosystem services;
4. Learned societies and industrial partners should promote opportunities, skills and careers in soils and sustainable agriculture at all levels from post-11 education to continuing professional development to secure the intellectual and skills base to meet the urgent challenges outlined in this report.

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1 Introduction

This report is the outcome of a workshop, 'Optimising Soil Chemistry for Agriculture and Resource Efficiency (OSCAR)', held at the Royal Society of Chemistry, Burlington House, London in 2011.

The aim of the workshop was to bring together researchers, policymakers and industrial stakeholders to examine the key challenges that we face in the area of soil sustainability, which is crucial to meeting the global challenge of food security and delivering the objective of sustainable intensification of agriculture. In particular the participants aimed to identify critical elements where chemistry, in partnership with other disciplines, can help to provide solutions to the key research challenges.

The workshop was initiated to deliver knowledge exchange as part of a NERC Consortium Grant on biological weathering and soil nutrient dynamics, led by the University of Sheffield. The event was jointly organised by the Royal Society of Chemistry (RSC), the University of Sheffield, the Natural Environment Research Council (NERC) and the Environmental Sustainability Knowledge Transfer Network (ESKTN). This report brings together the research presented at and recommendations from this workshop.

2 Background

Food security is one of the great global challenges of the 21st century that will require solutions on the time scale of only a few decades. The global population grew to seven billion in 2011, and by 2050 it is expected to reach over nine billion. However, the resources to feed this growing population are limited. In 1960, one hectare of land produced enough food to feed two people; by 2050, the same amount of land will need to feed more than six people.[2]

Soil is essential to the production of food but has many other important functions, delivering a variety of ecosystem services. These include the storage, transmission and filtration of water; the transformation of nutrients; the storage and emission of greenhouse gases including carbon dioxide and nitrogen oxides; the role of soil as a substrate for construction; the processing of waste materials; and the position of soil as the sustaining medium for all terrestrial ecosystems.

Despite this critical role in supporting human and natural communities, major questions regarding the functioning, stability and evolution of soil remain unanswered. Soil science is a challenging field; this most complex of materials requires integration of skills from both fundamental and applied disciplines. The spatial variation of soil even within a small area makes it difficult to scale from pores (where biogeochemical reactions take place) to profiles and field scales, where management activities can be applied.

The unique location of any unit of soil within a landscape exerts control on its dynamic behaviour and its responses to any perturbation. Every block of soil is a timed 'memory' of past and present biosphere-geosphere dynamics at that location.[3] This leads to difficulties in the management of soil health on the scales necessary to help increase agricultural productivity and, of equal or greater concern, a lack of confidence in decision-making on how to protect and conserve soil stocks which are globally declining, due to a combination of different processes, for example erosion and dispersion.[4]

The pressure on soils is significant and growing. A concerted response is required from researchers, politicians and land users across a broad range of research disciplines, jurisdictions and commercial markets, to ensure that soils are protected and enhanced.

2.1 The UK soils research landscape

Table 1 lists the key reports related to soil research in the UK published since 2008. Appendix 1 presents a summary of the key points from each of these publications, providing the overall background to the development of the OSCAR workshop in November 2011.

Table 1: The UK landscape for soils research, 2008 to present.

Royal Agricultural Society of England, 2008, 2010. The RASE 'Practice with Science' group championed soil as a vital resource, jointly neglected by the government, the research community and land managers. These reports recommended a common strategy for soil research and development, and warned against a persistent lack of shared vision which threatens the capability of UK soil research to underpin future industry performance.	Godwin R, Spoor G, Finney B, Hann M and Davies B (2008) *The Current Status of Soil and Water Management in England*. Practice with Science Group, Royal Agricultural Society of England. Kibblewhite MG, Deeks LK and Clarke MA (2010). *A Gap Analysis on the Future Requirements of Soil and Water Management in England*. Practice with Science Group, Royal Agricultural Society of England.
Royal Society of Chemistry, 2009. Food and agricultural productivity were key themes in the 2009 Roadmap. Fundamental and applied chemistry are key parts of the solution to match energy and food demand with limited natural resources.	Royal Society of Chemistry (2009). Chemistry for Tomorrow's World: a Roadmap for the chemical sciences.
UK Government Office for Science, 2010, 2011. Two key reports by the Foresight programme highlighted the broad range of ecosystem services supplied by high quality land resources, and outlined the need for revitalised fundamental R&D in soils and food security.	UK Government Office for Science. (2010). *Foresight Land Use Futures Project*. UK Government Office for Science. (2011). *Foresight. The Future of Food and Farming*.
UK National Ecosystem Assessment (NEA), 2011. The NEA confirmed the importance of soil ecosystem services particularly in supporting and regulating the more widely recognised provisioning services. It further highlighted the high degree of uncertainty surrounding these key ecosystem processes and the need for more, and better, environmental data.	UK National Ecosystem Assessment. (2011). The UK National Ecosystem Assessment Technical Report.
ESKTN/NERC: Soil Health and Sustainability, 2011. A multi-stakeholder consultation showed that there is considerable potential for greater collaboration and integration of research activities between research councils and other funding bodies. It also revealed a clear need to facilitate and enhance current activities for knowledge exchange (KE) and the dissemination and uptake of primary research by a much wider user community, from farmers and agricultural levy boards to consumers and developers.	Environmental Sustainability KTN & NERC. (2011) *Soil Health and Sustainability*.

Natural Environment White Paper (NEWP), 2011. Chapter 2 of the NEWP includes a specific section on soils which puts the cost to the economy of soil degradation at £150-250 million per annum.	HM Government. (2011). The Natural Choice: securing the value of nature – Section 2.6: Safeguarding our soils.
European Commission, 2012. The Joint Research Centre of the European Commission details the common problems across the EU in soil over-exploitation, degradation and loss. It calls for a greater awareness across society of the economic value and importance of soils.	Jones, A. et al. (2012). *The State of Soil in Europe*. JRC Reference Reports, European Environment Agency.

As a specific context for this report from the OSCAR workshop, pertinent to highlight worth highlighting the following extracts from the government's Natural Environment White Paper (2011):

Section 2.61 states:

By 2030 we want all of England's soils to be managed sustainably and degradation threats tackled successfully, in order to improve the quality of soils and to safeguard their ability to provide essential ecosystem services and functions for future generations.

It goes on to make the following commitment:

We will undertake a significant research programme over the next four years to explore how soil degradation can affect the soil's ability to support vital ecosystem services such as flood mitigation, carbon storage and nutrient cycling; and how best to manage our lowland peatlands in a way that supports efforts to tackle climate change. We will use the results of this research to set the direction of future action.

3 The OSCAR workshop, November 2011

Given the body of evidence summarised in Table 1 about the risks to UK soils, as well as to the UK soil science research base, the Royal Society of Chemistry, NERC and the ESKTN wanted to focus on the role of chemistry in addressing some of these key challenges, and to initiate a discussion on possible solutions, in the form of developing novel research collaborations.

Day One reviewed the current state of soil science across academia and industry with a focused discussion looking at the key challenges that need to be faced in the future of soil science. The final keynote presentation highlighting the UK political landscape in the area of agriculture was given by Professor Sir Bob Watson FRS, Defra.

Day Two of the workshop focused on resource sustainability, in particular phosphorus scarcity, with a discussion on the key challenges to society and to R&D in this area. The second part of the day focused on some of the solutions that chemistry can deliver in this area, particularly in the areas of environmental sensing and 'smart' chemical agents. The workshop concluded by developing a set of collaborative project ideas based around critical research priorities for soils and food security.

The workshop was attended by around 50 delegates representing research institutions from across the UK. There were also representatives from the European Commission, agrochemical industry, SMEs and funding bodies including RCUK, NERC, TSB and Defra. A full programme and list of speakers contributing to the workshop is appended to this report. The following is a record of the discussions and plenary presentations.

3.1 OSCAR plenaries: the state of soil science

Soil is the fundamental life-support system for the terrestrial environment.

Humans, like the rest of the terrestrial biosphere, are intimately connected to and wholly dependent upon soil.[a] All of the atoms of our bodies are borrowed from the soil or atmosphere – we are incipient compost.[5] Yet this most important natural resource has been treated like dirt. Nearly 33% of the world's arable land has been lost to erosion or pollution in the last 40 years. This erosion, which can occur at 10-100 times the rates of soil formation, leads to the preferential removal of organic matter and clay, removing soil nutrients and releasing CO_2.[4] These losses under current intensities of agricultural activity are unsustainable. Without better understanding and management of our soils, the demands for intensification of agriculture over the next decades may be disastrous.

Soils form the interface between the biosphere, geosphere and atmosphere and hence play a key role in global geochemical cycles, including the geological carbon cycle, and in the regulation of global temperature. The NERC-funded weathering science consortium work led by the University of Sheffield as part of an extended programme of research in this area, has revealed the central role of the co-evolution of plants and soil fungi symbionts in geochemical cycles and palaeoclimate dynamics over geological time.[b] These symbioses, which are found in over 80% of plant species, support the uptake of nutrients by plants and in doing so contribute significantly to the weathering of minerals and the formation of soils.

The cutting edge of current research is in the determination of the mechanisms behind these biogeochemical processes in soils and understanding how they contribute to soil fertility, stability and resilience under changing land use and agricultural practice. NERC-funded collaborations between universities at Sheffield, Bristol and Leeds have applied co-ordinated biological experiments and state-of-the-art geochemical analyses to understand how plant-fungi symbionts direct energy from photosynthesis into the soil to drive mineral weathering.

The research has shown co-ordinated root and fungal responses to soil mineralogy – biosensing activity to stimulate fungal growth, energy consumption and weathering activity around specific sites containing nutrient-rich minerals. The micron-scale hyphae of fungi seek direct contact with mineral surfaces and apply physical pressure and chemical conditions (for example lowering pH) to stimulate nutrient release.[6] This physically degrades and roughens mineral surfaces, leaving them permanently more vulnerable to weathering. This strong participation of plants and symbiotic fungi in mineral weathering is now proposed to be a major control on flows of carbon, water and nutrients throughout the rhizosphere (plant root zone).[7]

[a] *Comment and discussions relating to Prof Jonathan Leake's presentation*
[b] *Comment and discussions relating to Prof Steven Banwart's presentation*

Soil carbon is a critical component of the global carbon cycle.[c] The store of carbon at the land surface is around 1.5 times that of the surface regions of oceans and the atmosphere combined. The 450 trillion kg of carbon in boreal forest soils alone equals the total carbon content of terrestrial plant life. The annual fluxes of carbon between the terrestrial environment and atmosphere are one third more than exchanges between the oceans and atmosphere and more than 18 times the annual release of carbon from fossil fuels although critically the latter is uncompensated. The annual cycle of carbon fluxes to and from the terrestrial environment is clearly apparent in the atmospheric carbon signal. The potential impact on climate change of deterioration in soil's capacity to store carbon is therefore highly significant.

Recording and monitoring changes in soil carbon stocks is difficult, although comprehensive datasets now exist for the UK and for the European Union (EU).[8] Critically, uniformity and spatiotemporal resolution are required in sampling and analytical methods. In the UK, these data allowed the first estimation of changes in soil carbon stocks at 5 x 5 km resolution over a 25 year period (1978-2003).[9] The results suggest that carbon has been lost from soils under a range of land uses, with high-carbon soils experiencing largest rates of change. These changes coincide with apparent long-term rise in soil pH by up to 0.04.[10] However, the data reported in the 2007 UK Countryside Survey does not reveal the same picture, so there is still some controversy about the rate of carbon loss in UK soils.[11]

The current state of the science in elucidating the drivers and controls on these changes include the coupling of first order multiple-pool models for soil carbon and nitrogen with isotope analyses to isolate and quantify the rates of exchange of carbon and nitrogen within different components of the plant-soil system.[c] Current models are limited by semi-empirical parameterisation and the omission of key processes including the influence of soil biological processes on carbon and nitrogen fluxes and transformations. Critical to improvement in these models is continuing long-term, fit-for-purpose soil monitoring; better, physically-based soil carbon and nitrogen models; and new methods to integrate models and data across spatial and temporal scales.

The UK-led SoilTrEC consortium is co-ordinating EU research efforts to integrate detailed scientific understanding of soil structure and function with modelling and management of soil ecosystem services[12,d]. The approach is to integrate existing and new datasets across a nested range of scales within a life-cycle model of soil formation and evolution, using a set of new European Critical Zone Observatories.

The central objective is to provide a modelling framework which can delineate soil threats and assess mitigation at EU scale by quantifying the impacts of changing land use, climate and biodiversity on soil function and economic value. The vision is to enable the design of sustainable land use through computational simulations of soil structure evolution in response to water flows, geochemical transformations, carbon dynamics and ecology.

The critical challenge is to organise and synchronise the large but disperse existing datasets on soil processes across temporal and spatial scales to provide tools for valuation, scenario analysis and forward planning by land managers and policymakers.[13]

The major new insights into biogeochemical functioning of soils and their wider roles in earth systems now being made must be employed to better inform the valuation and management of soils and the ecosystem services they provide. The EU Thematic Strategy for Soil Protection summarises these services as food and fibre production; filtering water; transforming nutrients; carbon storage; biological habitat; and the soil gene pool.[14]

These crucial services are central to meeting the UN Millennium Development Goals to end poverty and hunger, to reduce the rate of biodiversity loss, and to increase access to basic drinking water and sanitation. Threats to soils directly translate into threats to these major international humanitarian objectives.

[c] *Discussions made around Prof Guy Kirk's presentation*
[d] *Discussions made around Prof Steven Banwart's presentation*

3.2 OSCAR plenaries: resource sustainability

Soils security, food security and sustainable agriculture are intimately related. Agricultural intensification made possible the rapid expansion of the world population since 1945, but the cost to soils and connected water resources has been substantial. The dependence on global markets for both raw materials and end products in the food supply chain is now of serious concern.[e]

Although the reserves of the major agricultural nutrients nitrogen, phosphorus and potassium (NPK) are not immediately threatened (current rates of consumption will see 11% of known P reserves exhausted by 2050), costs are highly vulnerable to global market fluctuations and changing geopolitical landscapes. This has impacts right along the food supply chain.[e]

Advancing fundamental understanding of soils is vital to ensure land remains productive, but equally important is the development of new technologies to minimise waste and maximise recovery from waste of finite, high-value resources used in agriculture. Reduction in costs, and collateral environmental impacts, and the development of accessible technologies for doing so, are all critical objectives of the sustainable agricultural revolution that is needed to achieve global food security. This revolution will need to be implemented by communities in all parts of the world.[f]

Agricultural resource efficiency is therefore a key component in engineering this revolution. New methods are required which reduce costs by minimising the quantities of agrochemicals used, by targeted application, enhanced uptake, reduced run-off and recovery of nutrients from waste streams throughout the food chain. These objectives rely on sophisticated understanding of the transport, interactions and fate of chemical agents within the plant-soil system – something which is only crudely addressed by the source-pathway-receptor concept underpinning current environmental risk assessments.

A central challenge for chemical sciences is the development of new ways to recover high-grade NPK and other nutrients from low-grade (diffuse and dirty) agricultural and other waste streams. Current developed-world agricultural practice requires 22.5 kg potassium to deliver a typical 0.44 kg dietary potassium level per person per annum.[g] Similar calculations can readily be performed for water, energy and other minerals consumed in food production. Such significant inefficiencies nevertheless represent a substantial quantity of potentially recyclable raw materials available to be 'mined' at various points from along the supply chain, if we can develop efficient technologies and systems for recovery.

A new, whole-system, conceptual model is needed for resource use and recovery across the food chain, informed by high-quality science that enables a shift in regulatory and market paradigms towards prevention and recycling, rather than remediation and disposal, of agricultural wastes. The opportunity to create marketable resources from waste P is demonstrated by innovative companies such as Ostara (Vancouver, Canada) that 'harvests' nutrients from municipal wastewater and uses them to produce fertiliser.[15] Realising this integrated, closed-loop approach to resource management is dependent on the development of cross-disciplinary capability in soil, environmental and chemical sciences to establish the basis for the new technologies to achieve the objectives outlined above. This in turn depends on more investment by a variety of stakeholders to enable these developments.[h]

[e] *Discussions made around Dr Albino Maggio's presentation*
[f] *Discussions made around Prof Sir Robert Watson's presentation*
[g] *Discussions made around Dr Richard Miller's presentation*
[h] *Discussions made around Mr Calum Murray's presentation*

One area in which the UK has particular scientific strength is in environmental nanotechnology. The range of potential applications in pursuit of 'smart' agrochemicals, environmental sensor technology and waste remediation is substantial (Figure 1).[i]

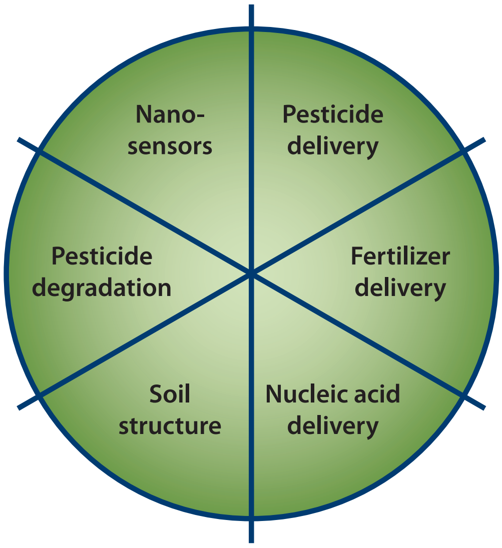

Figure 1. Six core targets for nanotechnology in agriculture. Based on Ghormade et al. (2011)[16]

In soils, the nanoscale chemical environment and interactions within the immediate space around roots, as a result of plant and microbial metabolism and pore geochemistry, are of huge significance in the optimisation of plant nutrient and agrochemical uptake and hence crop management. Nanoparticles with a wide range of compositions and structure can cross plant cell walls and so provide a potential delivery mechanism for targeted application of chemicals to plant roots.[17] However, the mobility, fate, uptake rates and biological effects of nanoparticles are likely to be highly sensitive to local biogeochemical conditions and a major research effort is required to robustly understand their implications for soil and agricultural environments in parallel with the development of novel particle functions and architectures.

There remains considerable scope for focused research on nanoparticulate delivery agents and the dynamics of nanoscale rhizosphere environments. Nanoscale research is also providing detailed insight into the 'technologies' that plants themselves use to absorb and process water and chemicals, offering the potential for the design of agricultural products which are optimised to work with specific plant architectures, or materials designed to mimic high-efficiency biological systems (for example, solar cells based on leaf photosynthesis).

Progress in all these areas is contingent on further developments in analytical technologies at the nanoscale, particularly in the identification and quantification of chemical species (inorganic and organic), the size of, and charge distributions on, macromolecules, particles and surfaces, and the imaging of dynamic chemical environments around individual roots and plant tissues. The UK has internationally-leading capabilities in environmental nanotechnology, particularly those available through the NERC Facility for Environmental Nanoparticle Analysis and Characterisation (FENAC) at the University of Birmingham, and the Oxford University Begbroke Science Park. Begbroke hosts a number of chemistry innovation SMEs, including Oxford Advanced Surfaces which has already conducted pilot projects in the area, of surface-optimised particulate delivery agents for agricultural herbicide.

In the context of a rapidly growing world population, limiting natural resources and progressive environmental change, the preservation and optimisation of soils for agriculture and other critical ecosystem services presents a grand challenge for the chemical sciences.[k] From the development of sensors, to better probe the dynamic soil environment, through to smart agrochemicals designed to work with specific soil and plant architectures, and innovative processes to recover resources from waste and securely store carbon, there are potential opportunities for chemistry generate new technological applications.

But, soils are highly complex, technically difficult to analyse, and – critically – unfashionable. The current progress in soil science and technology, in which the UK plays a leading role, promises significant advances in our ability to understand and work with the complexity of soils. However, it is the third challenge, the perception of soils in society, that requires urgent action: to secure not only the next generation of soil scientists and managers, but the public recognition and valuation of soil health and sustainability as the fundamental basis for global food security in the 21st century.

[i] *Discussions made around Prof Peter Dobson's presentation*
[j] *Discussions made around Dr Garath Wakefield's presentation*
[k] *Discussions made around Dr David Lawrence's presentation*

4 Workshop outputs

4.1 SWOT analysis for UK soils and agriculture

The workshop participants conducted a strengths, weaknesses, opportunities and threats (SWOT) exercise to evaluate the current state of the UK's capability in the areas of soil science, food security and agricultural sustainability. Participants were divided into four groups. The outputs from each group were subsequently combined and ranked to identify the most common factors, presented below.

4.2 UK strengths in linking soil science, food security and agricultural sustainability

1. Continued investment from multinational agrochemical and fertiliser industries.
2. Strong agricultural consultancy industry and professional networks in soils.
3. Strengths in applying research and technological innovation to agriculture through agricultural research institutions and experimental farms.
4. International leadership in research on the chemistry of climate change and terrestrial-atmosphere geochemical coupling.
5. Large extant collections of environmental data available for data mining and longitudinal analysis.

The UK is an important R&D and production location for multinational agricultural technology companies. For example, Syngenta maintains its primary chemicals collection in the UK and operates centres for discovery chemistry to identify active ingredients and biosciences research to develop them towards potential production as agricultural chemicals.[18] Yara, the major global supplier of fertilisers, operates manufacturing and distribution centres at a number of UK sites and also bases research and expertise in foliar and micronutrient fertilisers, as well as global analytical services, in the UK.[19]

These and other knowledge-based industrial resources represent high-value intellectual capital investment in UK R&D. The global agrochemical industry recognises the challenges and importance of improving our understanding of soils, with the aim of producing more effective, more efficient, lower-waste products driving a move towards more intelligent site-specific agriculture. This strong message indicates a basis for engagement with industry.

The UK base of professional soil scientists and agricultural consultancy is strong and maintained through support provided from organisations such as the British Society of Soil Science, Institute of Professional Soil Scientists, and the Royal Agricultural Society of England. The body of professionals is supplied by graduates from specialist soils and agriculture courses provided at research institutes throughout England, Scotland and Wales.

There are also well-established means for farmers and land managers to engage with environmentally-sustainable farming methods. Organisations such as LEAF (Linking Environment and Farming) encourage operation of farms to stringent Integrated Farm Management criteria. A network of Demonstration Farms acts as a mechanism for knowledge exchange.[20] These complement a series of experimental farms and instrumented catchments operated by universities, industry and research councils.[21] Emerging UK leadership on the international stage in this area is evidenced by the establishment of global networks of research field sites and major new collaborations such as the European Commission and USA National Science Foundation Critical Zone Observatories, the UK Environmental Change Network and the NERC Environmental Virtual Observatory Programme.[22,23,24]

The UK's international standing in research excellence is particularly strong in the area of climate change, for example the Tyndall Centre for Climate Change Research spanning eight UK research institutions, and the Meteorological Office Hadley Centre. These high public profile institutes are complemented by internationally-leading research in soil carbon and nitrogen dynamics. This includes the impact of land use on gas exchanges between the soil and atmosphere, supporting research into the impact of agricultural policy on climate change.[I] UK research institutions additionally host databases containing unrivalled detail on the spatial and temporal characteristics of UK soils. In particular, the National Soil Resources Institute at Cranfield University stores the definitive national soils inventory. This comprises spatial mapping of soils at a variety of scales, as well as corresponding soil property and agro-climatological data. The web-enabled service is the largest of its kind in Europe.[25]

[I] *Discussions made around Prof Guy Kirk's presentation*

In summary, the UK has strong communities of industrial, professional and academic soil experts, together with internationally-leading research institutes and data collections. As evidenced above, this can lead to major new global initiatives and collaboration. As a result, it should be well-placed to respond to strategic initiatives in soils, food security and sustainability research.

4.3 UK weaknesses in linking soil science, food security and agricultural sustainability

1. Often poor communication between the academic and industrial knowledge base.
2. Lack of clear priorities on sustainability both in academic science and industrial R&D.
3. Constrictive/precautionary regulatory framework which can restrict innovation.
4. High costs of developing, commercialising and marketing new technologies.
5. Excessive concentration of effort on mediating the worst effects of current practice rather than on realising new, more sustainable protocols.
6. Mismatch between the UK agri-industry and global agricultural needs/markets.
7. For SMEs, an inability to pursue and successfully realise niche economic potential in soils and agriculture R&D.
8. Fragmentation of science research base among different disciplines, competing institutions and research councils operating with strict limits on remit and research priorities.

Despite UK strengths in individual research spheres, the workshop perceived a relative paucity of communication between soils researchers in academic and industrial organisations. While it is difficult to pursue this issue quantitatively without a detailed survey, it might be argued that the current concentration of knowledge exchange (KE) activity in the areas of environmental sustainability, biosciences, food security and soils from the TSB and research councils represents an acknowledgement of a need to develop this area.

The perception is that sustainability does not take clear priority in either academic or industrial R&D. The evidence from presentations made at the OSCAR workshop, along with stated objectives from research funding programmes, highlight otherwise. Research centres and institutes across the UK, as well as the UK leadership in significant new international initiatives, also support a different conclusion. However, it is possible that both these comments reflect a practical discontinuity between aspiration and action on sustainability or may be due to lack of communication.

The 'valley of death' between research outputs and practical application in society (eg by commercialisation) has a high public and political profile in 2012 and its relevance in the drive for food and soil security is as great as in other sectors.[26] Engagement between academic and commercial sectors to drive innovation may be obstructed by prohibitive regulation and the high costs of developing products from idea to market.[m] These factors are synergistic. A commercial agrochemical product may cost $100m in health and safety testing before coming to market. Yet, it is widely recognised that the laboratory tests required by regulations, particularly those relating to environmental hazards and impacts, can be poorly representative of real-world soil, water and ecosystem responses. The potential conflicts between legislation and policy drivers for innovation and environmental/health objectives are well known and, with the co-ordination of legislation across the European Union, not unique to the UK. However, these facts do not mitigate the issue.[27]

The strategic capital required to bring products through the regulatory process reserves much of the market for large multinationals. Small and medium-sized businesses (SMEs) do not have the same resources and must respond to immediate customer needs. They cannot undertake R&D on products that require long periods of time for testing, acceptance and market penetration. Nevertheless SMEs, many starting as spin-out companies from universities, are often those operating closest to academic researchers and research institutes, through co-location on campuses or science parks or via the roles of academics and university researchers in the

[m] *Discussions made around Dr Ray Elliott's presentation*

management of the SMEs themselves. Conceptually, they are therefore best placed to act as a pathway for innovation in soils, food and agricultural technology but there is a strongly perceived lack of financial incentive or support, further compromised by the lack of clear near-term market opportunities.[n]

In summary, the recognised areas of international research and professional expertise in soils and agriculture in the UK appear to be prevented from effectively working together. This is through a combination of financial, regulatory and strategic disincentives which must be overcome in order to achieve the goals of food and soil security.

4.4 UK opportunities in linking soil science, food security and agricultural sustainability

- Develop an educated, interdisciplinary community of graduates in soil biogeochemistry and sustainable land management.
- Engage science and engineering students with 'blue skies' research eg complex systems and 'real-world' environmental and sustainability problems.
- Develop new models for KE in soils and agriculture that may lead to a better understanding and a greater acceptance of risk and long-term returns rather than short-term outcomes.
- Engage with the world-leading UK socioeconomic research base in sustainable development policy.
- Proactive development of the rural land-use planning framework, eg the recommendations of the Land Use Futures Foresight group.
- Leverage soils and agri-chemistry for nutrition and human health policy objectives.

The workshop participants proposed several areas of opportunity which were broadly agreed upon across several, breakout groups. The key weaknesses that these opportunities target are those around communication and engagement between different research specialisms and sectors, and the legislative and policy landscape. Within all these areas progress on soils and food security must be achieved to meet the challenges so communication is key.

Education of a new generation of scientists and professionals in plant, soil and land management is a critical step. Through the 1990s a fragmentation of soil biology from soil chemistry and soil physics took place, with biology joining plant science in leading the agricultural biotechnology research movement. At the same time, physics and chemistry moved successfully towards macro-environmental issues such as climate change and pollution.

Both these areas reinvigorated interest in soils, countering a perceived decline in soil sciences, a fact clearly identified as long ago as 2005 in a report to government by the Agriculture and Environment Biotechnology Commission (AEBC).[28] However, the same report warns that this move to specialisation in soil scientists being educated today may result in an irreversible and damaging loss of expertise necessary to address the multidisciplinary agenda that is required for soil science. In particular, the AEBC report continues 'there are some important agricultural soil science questions that are in danger of being neglected'.[28]

The OSCAR workshop outputs highlight that, almost seven years on, both industrial and academic researchers still prioritise this concern. Plant biotechnology is increasingly looking to the functional biogeochemistry of the root-zone (rhizosphere) as a target for further crop optimisation and finding the research base knowledge, technology and skills to be a crucial limitation.[29,30] Similarly, researchers working to understand the broader environmental role of soils in global biogeochemical cycles and climate change are increasingly aware that the biology and complexity of the rhizosphere may be a critical control especially when focusing on the functional responses of soils at larger spatial and temporal scales.

[n] *Discussions made around Dr Gareth Wakefield's presentation*

In recent years very few research programmes have required both soil and plant science to work together. However there are now emerging drivers to develop researchers and professionals cogent in the whole soil system. The RCUK Global Food Security Programme is driving forward challenge-led interdisciplinary R&D. Universities currently have strong incentives to review course structures and invest in teaching and research areas with strong industry links and clear socioeconomic relevance. There is a strong opportunity for the case for interdisciplinary soil science to be heard. Even within current discipline structures for teaching, there are strong calls for greater exposure of scientists and engineers both to the frontiers of 'blue skies' research and to real world problems, with the aim of building skills and thinking in innovation.[31] Soils and food security provides a clear target for such interdisciplinary initiatives.

Engagement between academic, policy-led and industrial R&D is a key challenge. The Technology Strategy Board and its cohort of Knowledge Transfer Networks provide a focus for work in this area, supported by the KE programmes of the major research councils and government agencies. This is a well-established KE infrastructure; the TSB co-ordinated more than £2bn investment in innovation in the UK between 2008-2011.[32] The current TSB strategy explicitly recognises the long pathway from concept to commercialisation (while not explicitly acknowledging the equally long process of scientific development before a concept can be proposed) and outlines a framework of support to progress innovations along that pathway. The TSB maintains a Sustainable Agriculture and Food Innovation Platform which aims to programme investment worth more than £90m between 2009-2014. Core support comes jointly from the TSB, Defra and the Biotechnology and Biological Sciences Research Council (BBSRC).

This infrastructure provides a significant opportunity to build industrial KE around food, soils and sustainable agriculture. It is complemented by investments from NERC and RCUK in this area, including the Rural Economy and Land Use (RELU) programme. In both industrial and policy spheres, the challenge is to move towards models in which risks are transparent, quantified and accepted and investment is made towards long-term returns rather than short-term outcomes.

The RELU programme provides a celebrated example of the benefits and successes of environmental sciences with social science researchers.[33] A collaboration within RCUK between the Economic and Social Research Council (ESRC), BBSRC and NERC, the programme enables researchers to work together to investigate the social, economic, environmental and technological challenges faced by rural areas. Many of the projects within RELU have addressed areas of soil science, sustainable agricultural practice and food security, but not the detailed multidisciplinary science that underpins these.

Another example of cross-council funding was the Environment & Human Health (E&HH) programme which operated between 2007 and 2009.[34] In this case the objective was to assess environmental systems from the perspective of their impacts on health economies, based primarily around small workshop and working group projects drawing together researchers from both discipline areas. The projects within E&HH led to initiation of some major directed funding programmes within the research councils. They established a model for the benefits of streaming research funding from the health and social sectors towards root-cause problems in the environmental sciences.

Furthermore, UK science provides significant leadership within major European Commission programmes to deliver interdisciplinary R&D solutions to policy challenges outlined in the EU Thematic Strategy for Soil Protection.[35] Two major programmes are SoilTrEC and EcoFINDERS. Both are large integrating projects, collectively equivalent in scope to an RCUK programme. Within these projects, natural sciences and social sciences are intertwined to quantify soil ecosystem services, and their monetary valuation. The approaches of these projects aim to guide policy approaches to mitigate costs and capture opportunities for soil and land management where costs and benefits lie outside existing markets.

In summary, the infrastructure support put in place provides a strong basis for developing interdisciplinary and cross-sector engagement in soils and sustainable agriculture. This has been provided by the TSB and RCUK and the operational models represented by RELU, E&HH and European projects. There are clear opportunities to build on the networks and funding models developed through these UK and European projects to structure a new round of research programming focused on the pressing, and often directly related, soil science issues discussed here. The Living with Environmental Change (LWEC) partnership also offers opportunities for further collaborative, cross-cutting projects to be taken forward, with the appointment of the deputy director of RELU to a new LWEC Research Fellowship in Land Use.

The new focus on soil and food security allows the development of a strong case for integrated teaching of soil science to provide a generation of researchers and professionals capable of taking on the challenges outlined by the OSCAR workshop.

4.5 Threats to progress and impact of UK R&D in linking soil science, food security and agricultural sustainability

- The inherent complexity of soil systems and of natural resource lifecycles.
- Persistent inability to fund long-term research towards interdisciplinary solutions.
- Restrictions on funding calls and competition for relatively scarce funding pots.
- Competition from 'higher priority' social agendas, particularly against rising energy demand, proscriptive legislation and continued stress on the wider economy.
- The need to drive behavioural changes in consumers of food and other ecosystem services; without which there are few industrial incentives to shift current practice.
- Challenge of creating globally marketable products in sustainable agriculture.
- Inability to engage international competitors/ regulators in driving paradigm shifts across national and continental boundaries.

The threats identified during the OSCAR workshop focus strongly on the possibility that the UK drivers for research in soils and agricultural sustainability cannot be framed with sufficient clarity. It was felt that the case for substantial investment in new research in this area would not be communicated with sufficient force to win the battle for national funding, either in the industrial or research sectors, against other socioeconomic challenges or commercial markets. Nationally and globally the socioeconomic climate for the foreseeable future would appear to be one of austerity, focusing the political agenda, and perhaps in consequence the priorities attached to research funding, away from long-term environmental research where the returns are widely separated from the investment. However, some mitigation of these concerns may be found in the strong UK presence in current R&D programmes of the European Commission and in the strength of science leadership in the direction of research resource allocation in the UK.

The complexities of soil as a global resource – under threat on a global scale – means that technological or management solutions developed and applied in one country or region may not be suitable for another, due to differences in finances, infrastructure, agricultural practice and political landscapes as much as environmental variation.

This set of challenges is faced not so much by the scientific community that, despite the specific structural issues detailed in this document, is by its nature collaborative and able to co-ordinate research progress on an international scale. It is faced by authorities and companies attempting to develop applications of science that can be rolled out worldwide. If the costs of developing a product for one market are large, the costs of adapting it to the demands of markets throughout the world are many times greater. The international challenges in political direction of environmental policy can be seen in disagreements over a proposed Soils Framework Directive in the EU, and by proxy the now 20-year-old UN negotiations on environment, climate and sustainable development ongoing through the recent Rio Earth Summit 2012.

The threats to soils research in the UK, and to its effective impact in achieving sustainable management of soils as agriculture intensifies in the next 40 years, are rooted in:

- A failure to monetise soil ecosystem services or to otherwise integrate soil resources within economic analyses;
- The general public perception of environmental priorities as separate from (and secondary to) social and economic needs;
- Wider global inequalities of wealth, health, resources and aspiration.

The call for concerted action to address threats to soils must therefore be framed in terms that will be heard not just by scientists from across disciplines, but by economists, politicians, businesses and citizens worldwide. The effective application of the science proposed here will require significant engagement with all these groups.

5 Recommendations

The OSCAR workshop outcomes identify a series of high-priority, high-impact objectives for research and science-led strategy development to address the urgent needs of soil and food security and agricultural sustainability.

5.1 Applied research priorities in soil and agriculture

Meeting attendees identified four future projects that offer the potential to provide solutions to ensure there is adequate soil management in the future:

1. Creation of closed loop systems for recovery of major nutrients, water and micronutrients from low-grade farm and food wastes to reduce dependence on primary stocks and global markets;
2. Development and application of high sensitivity, high resolution biosignalling and sensor technologies to support precision agriculture and more sophisticated regulatory testing;
3. Detailed and robust understanding of molecular-scale biogeochemical processes associated with phosphorus uptake at and around plant roots, to stimulate the development of target-specific, 'smart' agrochemical agents;
4. Integrated models of plant-soil-water interactions and development of methodologies to upscale from laboratory to field and landscape to inform soil management policies, climate change mitigation and adaptation to environmental change.

5.2 Strategic objectives for soil science and agriculture

1. Establish a recognised and supported knowledge supply chain for sustainable agriculture and soil technology, connecting highly innovative R&D and SMEs with regulators, legislators and multinationals. This should be directed by the Knowledge Transfer Networks and learned societies;
2. The Royal Society of Chemistry should work along with other key professional institutions and scientists to promote soil sustainability and align soil science priorities with wider public environmental concerns;
3. RCUK and other research funders should expand interdisciplinary approaches to problems in soil conservation and sustainable agriculture by supporting engagement with economists and social scientists in identifying the key environmental datasets that underpin the valuation and budgeting of soil stocks and ecosystem services;
4. Learned societies and industrial partners should promote opportunities, skills and careers in soils and sustainable agriculture at all levels from post-11 education to continuing professional development to secure the intellectual and skills base to meet the urgent challenges outlined in this report.

These headline recommendations cut across scientific and engineering disciplines, funding remits, governmental and professional boundaries and industrial sectors. In the final sections of the report, we outline the implications and recommend priority activities for stakeholders in key sectors.

5.3 The food and agricultural sector

Soils are a fundamental, but largely off-balance-sheet resource which nevertheless sustain the entire food and agriculture sector from farm to fork. Meeting the urgent challenges outlined by the OSCAR workshop will not only ensure the sustainability of this resource and hence of the sector, but also presents a range of opportunities to significantly increase the value of the food supply chain while avoiding the impacts of negative societal responses to, for example, plant biotechnology.

The agricultural and horticultural industry need to engage strongly with others along the food supply chain (from agricultural machinery and fertiliser manufacturers, to distributors, processors and retailers) to be vociferous in drawing attention to the business risks posed by further loss of our key skills base in soil science R&D. These business risks include the increasing costs and changing regulatory burdens in Europe, driving innovation investment to move to other parts of the globe, coupled with the rapid development of the skills base in other regions such as South America and China.

Given the age profile of many of the active researchers in this area, we could soon lose our global leadership position in soil science, and with it the many opportunities for innovative products and services, with their accompanying patents and revenue generation potential in the international market. There is a substantial need for more, and more broadly-educated graduate researchers and professionals in soil science. An improvement in the recognition and reputation of soils security and global agricultural sustainability as a career specialism for highly-talented science students currently in further and higher education is also needed.

Industry across the agricultural sector should engage more closely with higher education institutions to determine ways in which to secure the future intellectual base for soil and agricultural science in the UK. Potential developments should include targeted internships, and funded postgraduate research aimed at reintegrating soil physics, biology and chemistry, coupled with knowledge exchange, updated programmes and development of more short courses.

Industry stakeholders should also work collectively with environmental NGOs, government and its agencies to develop investor and consumer awareness. This would be aimed at stimulating greater support for soil science as a vital element in our food security strategy. Agricultural products recognised as 'good for soil' potentially combine several marketing advantages: minimising inputs, minimising pollution, minimising waste and preserving ecosystems.

Businesses and investors along the food supply chain should both lobby for, and proactively support where appropriate, research in a range of applied and fundamental science areas critical to securing short-, medium- and long-term market opportunities and minimising risks. These include:

- investing substantially in technology R&D to enhance nutrient, water and energy recovery from farm and food waste streams and overcome barriers to deployment;
- increasing investment in research on sensor technologies to support enhanced understanding and management of soil-plant interactions, identifying and exploiting the significant opportunities offered by (bio)chemical signalling and high resolution separation technologies;
- supporting investment in fundamental research into rhizosphere biogeochemical processes, including the action of soil microbes and fungi, to optimise soil management and develop models for smart chemicals which take advantage of as-yet unidentified functional mechanisms of plant-soil interaction.

To support individual stakeholders to make these investments requires novel partnerships to be formed across the land management, agriculture and food supply sectors, promoting greater integration and uptake of primary research. We recommend implementation of a 'knowledge supply chain' in which clear pathways to impact and application for research and innovation can be established, and support mechanisms provided.

Such support should include proactive engagement by regulators and legislators to stimulate innovation in chemical technologies and management practice. Transparent accessible licensing and development pathways for R&D are vital to enable flexible and innovative SMEs to engage more readily with the established agri-environment marketplace.

In all of these there is a clear role for synergistic relationships between chemistry, biology, physics and engineering stakeholders, as well as economists, to deliver a step change in our food production systems, enhancing sustainability, maximising value and minimising economic and environmental risks.

5.4 Research strategy

Chemistry, alongside biology, physics and engineering, has a critical role in soil science. Chemists need to take on the challenge of using their skills to address problems in complex areas such as the deployment of physical techniques to determine soil structure, probing the mechanisms of nutrient cycling and understanding the chemical interactions between soil organisms and plants. The challenges described above all require a strongly interdisciplinary approach to achieve effective solutions. A key factor in improving outputs in soil science research is increased funding for cross-cutting and integrated research.

For example, research that encompasses both biology and chemistry in the rhizosphere and integration with geospatial science will allow new knowledge to be integrated into assessment and practices at field and landscape scale. We have a strong foundation within the UK of the many specific disciplines required. These provide a world-class platform for multidisciplinary partnerships that can be built upon to enable innovative solutions and make sure that such multidisciplinary research does not 'fall between the gaps'. There is a real opportunity to propel the UK to become a world leader in this area.

In Section 6 we present four priority research project outlines identified through the OSCAR workshop. These are characterised by their strong interdisciplinary nature. They couple fundamental physical, chemical and biological science with cutting edge technology and innovative new working practices. They have interest and advocacy from a wide range of science disciplines and with potential partners in HE, at national institutes, in industry and with government departments. These represent examples of innovative interdisciplinary research, addressing global-scale environmental and humanitarian priorities, which could be rolled out immediately, if funding is secured.

5.5 UK policy and legislation

The recent Natural Environment White Paper 2011 (NEWP) and the National Ecosystem Assessment (NEA) indicate that the UK government clearly recognises the overall importance of soil ecosystem services.[37] The growing significance of soils on the European environmental agenda, and the potential for real economic costs as a result of soil degradation and losses has been highlighted. Added to this is the fundamental role of soils in supporting the humanitarian objectives of the UN Millennium Development Goals. Investing in soil science to support food and sustainable agriculture presents the UK with opportunities for international leadership in development, industrial and environmental policy arenas.

Substantial improvements to our fundamental understanding of soil biogeochemical functioning are required to drive policy and land management decision-making, stimulate technological innovation and create opportunities for economic gains throughout the UK food and agriculture sector. Such science already underpins the RCUK Global Food Security programme and also the work being undertaken in the second phase of UK NEA which is now underway.

Having pledged £2 million over the next four years to help support the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES), the UK government is clearly committed to showing leadership in this area. The commitment in the NEWP to funding soils research through to 2015 is welcome and our identified priorities for science programmes in this area are outlined in this document.[38]

The strong business and financial interest in this area is shown by the development of The Economics of Ecosystems and Biodiversity (TEEB) initiative again with strong UK support, focused on valuing ecosystem services. There is a clear indication here that keeping research strength in this area will have long term advantages, maintaining an intellectual capital to support policy development and provide expert services to both industries and administrations.[39]

However, critical to maximising the impact of such research on UK sustainable development and economic performance, there will be measures to secure the translation of this research into products and expert services which can be exported worldwide. The UK has the opportunity to lead international policy and practice in sustainable agriculture in both the developed and the less-developed world by co-ordinated investment in both fundamental science and its translation to marketable and accessible technologies.

To secure these opportunities for the UK requires measures to overcome three substantial obstacles, identified by the OSCAR workshop and outlined in this report.

Firstly, there are serious challenges for the many innovative UK science and technology SMEs to access and capitalise on potential opportunities within the agri-environment sector. These SMEs operate close to the frontiers of scientific research in the UK and are well placed to take the first steps in translation of new knowledge into applied technology. There is a role for the TSB here and the KTNs could be funded to facilitate further developments of an effective 'knowledge supply chain' for food and agricultural technology. This combination would secure opportunities for SMEs by ensuring transparent markets and providing strong support for innovation in technology and practice at key points along the pathway from primary mineral production, through farm-to-fork, to waste and pollution management.

Secondly, and to support the first measure, an increase in the sophistication and flexibility of regulatory mechanisms for agrochemical and agricultural technology is required as a key step. We do not advocate a reduction in the rigour of testing for health and environmental protection during product development, but recommend a substantial and then ongoing review of testing and monitoring protocols to ensure that they maintain currency with rapid developments in environmental science and technology, particularly in the areas of soil biogeochemistry and chemical fate and transport in the environment. The recent (May 2012) call by Defra for a £3.3m science programme to underpin sustainable pesticides R&D is a welcome step forward here.

A parallel example from the UK water industry is the successful introduction of *Cryptosporidium* monitoring, which has stimulated cross-sector action to improve catchment management and resulted in measurable improvements to water quality and health, cementing the UK's global reputation in this field. This action exemplifies an integrated science-led regulatory approach leading to combined social, economic and environmental benefits.[40]

Finally, in the longer term, concerted action is required to secure the intellectual and skills set of soils and agriculture researchers and professionals in the UK through further and higher education. The skills pipeline in this area needs to be built up to ensure that scientists who have strength in different fields (biology, chemistry, physics and engineering), but maintain a interdisciplinary outlook to come together to address such challenges.

Investment in education of the next generation of soil scientists, making sure that they are equipped to work in a interdisciplinary environment is important. However, encouraging the next generation to consider soil science as a viable, challenging career is equally important. Research in soil science provides the opportunity to develop a career that will address one of the great global challenges of our time. It offers the opportunity to address complex problems that have the potential to deliver a real impact on our lives.

6.0 Priority research opportunities

The workshop identified four priority areas around which clear interdisciplinary research can be developed. The following project outlines, indicate the strength and depth of potential in each area. Each project is based on a substantial framework for rapid development, contains targeted key challenges in soil and agricultural sustainability, and is the basis for the development of long-term integrated programmes of research.

Project 1. Biosignalling and sensors

Focus of project: This project will aim to apply modern chemical, biochemical and molecular genetics techniques to the area of soil science, for example to explore the metabolomics of soil systems to determine the chemistry controlling communication between crop species and symbiotic soil organisms for improved nutrient supply and resistance to pests and pathogens. It will also aim to develop the sensitive detection of specific functional chemicals and nutrients in the soil, highlighting the dynamic changes in biogeochemical systems.

Proposed approach(es): The objective of the project is to engineer biogeochemical tools robust enough to operate in *in situ* soil conditions via a nanotechnology methodology, borrowing techniques and methodologies from modern analytical chemistry technology. The use of 'sentinel' plants and organisms with marker responses to particular signals will also allow monitoring of soil system states, to gain better understanding of the chemical and biological functions in the specific scenarios from above. The project would target the near root environment, where there is a wealth of chemical activity. Understanding the specific relationships between plant indicators and rhizosphere dynamics is critical. Biological organic and inorganic chemistry will be fundamental to understanding the processes occurring in the soil and therefore applications for chemical communication and improved nutrient-use efficiency to promote plant performance.

Research horizons: Being able to probe, monitor and understand the dynamic rhizosphere is critical to reduction of nutrient leaching, optimisation of plant nutrition and controlling the biological generation and exchange of greenhouse gases between soils and the atmosphere. Once there is a clear understanding of these relationships at the molecular level and which processes it affects, there is scope then to discover whether new relationships can be chemically or genetically engineered or whether existing relationships can be enhanced or introduced into the biochemistry of crop plants to take advantage of this and maximise crop performance. Relationships between the roots of conifers and fungi in a mycorrhiza community are already well documented and it is important to extend our detailed, quantitative understanding of these dynamic mutualistic relationships to arable crop systems and their rhizosphere microbiota to improve the performance of the plant.

Potential applications: By exploring these interactions in the soil environment, ways to enhance nutrients and/or water use and improve crop performance can be found, through 'fine-tuning' the plant-root environment and engineering the plant simultaneously. The project will provide the basis for the development of a new generation of small, robust sensors using nanotechnology for *in situ* soil and crop management - site specific agriculture. Enhanced understanding of rhizosphere biochemical and microbial dynamics will provide significant opportunities for the development of smart chemical agents which take advantage of chemical interactions between plants and their environments to optimise the delivery of nutrients, regulate pests and maintain plant health against macro-environmental stresses. This research area will additionally be of relevance to soil management and prediction of responses to environmental change, as well as engineering applications in landscape restoration and biological remediation of contaminated land.

Potential non-academic partners: Agronomists, agrochemical industry R&D, innovative chemistry SMEs, environmental consultancies, contaminated land managers, water industry, regulatory agencies. There is a requirement to understand the communication between plants, organisms and the soil environment. Understanding the symbiotic relationships between all the species present in a soil community at the root environment leads to the start of creating target specific sensors. The scope of this project is to inevitably develop experiments and probes that will provide the tools to monitor and enhance nutrient transfers in varying soil environments. This project should provide a database of results with opportunities for SMEs to produce novel probes that can support further academic research in the area, providing technical tools for farmers.

Project leads at the OSCAR workshop: Dr. Tony Hooper, Rothamsted Research; Prof. Peter Dobson, Begbrooke Science Park, Oxford.

Project 2. Closed-loop systems for recovering nutrients from waste

Focus of project: The aim of this project is to allow society to close the loop between the farm, the kitchen, the supported population, and the organic waste generated. With the intent of providing a safe and beneficial means of returning carbon and nutrients, particularly phosphorus (P), to productive land. Phosphorus and nitrogen (N) are essential to, and limiting for, the growth of organisms. Thus agricultural yields are enhanced by application of fertilisers. However fertilisation of aquatic plants (algae, etc), by loss of nutrients from the land or other sources, can cause significant environmental harm by eutrophication. Also the production of fertilisers is energy intensive and currently relies on non-renewable resources such as fossil fuels and rock phosphate, which are becoming increasingly scarce and expensive.

To deliver a low-carbon and more sustainable future, it is imperative that ways to recover nutrients from waste streams and produce fertilisers from this renewable source are found. The planet's reserves of phosphate are being mined at an alarming rate; today's mines will potentially be exhausted by the end of this century and estimates of future reserves are only 300 to 400 years at the current rate of extraction and so it is vital the P is recycled.[41,42] This estimation is based on the known quantities of rock reserves, whereas fertilizer production currently relies on the soft rock being processed. At present, the soft rock reservations have a considerably shorter predicted life span and are subject to rapid fluctuations in cost.

With regards to threats to the human population, phosphate should be considered as similar to climate change. Life on Earth with a different climate might be difficult but life without phosphate will be impossible. At present, without fertilisers about half of the current population can be supplied with sufficient food. With an increasing population there would be an even greater dependency.[43] Asimov (1974) summarised the importance of P as follows:

"…life can multiply until all the phosphorus is gone, and then there is an inexorable halt which nothing can prevent… We may be able to substitute nuclear power for coal, and plastics for wood, and yeast for meat, and friendliness for isolation - but for phosphorus there is neither substitute nor replacement." [44]

Conservation of Scarce Natural Resources is widely recognised on international political agendas with P being one of the elements under discussion. The proposed research area links to the EPSRC strategic priorities of energy (renewable energy – bioenergy) and engineering (resource efficiency and water engineering) and has strong links to the Living With Environmental Change (LWEC) theme, especially within the key elements of aqueous ecosystems and sustainability of resources. These areas are all EPSRC priorities related to new responses to changing environmental pressures including nutrient management, low carbon energy generation and food and water security. The proposed research also links to the Scottish Government's Rural and Environment Science and Analytical Services (RESAS) research programme 2011-2016, especially to theme 3 "Technologies and management tools to deliver greater benefits from rural land use and increased resilience to change".[45]

Proposed approach(es): Urine separation for direct use on agricultural land (eg energy crops) and for N and P recovery (eg struvite precipitation). Nutrient recovery from wastewater via algal biomass photosynthesis or photoreactive bacteria. Phosphorus recovery using inorganic sorption, for example iron-doped resins or nano-magnetite. Returning clean and safe nutrient sources back to the land, screening and removing heavy metals such as copper.

Research horizons: For urine separation in developed countries the research focus will be on socioeconomic barriers to uptake of the technology. Collection from dispersed sources is unlikely to be economically viable, and use as a fertiliser on food crops is unlikely to be socially acceptable but it is a source that could be processed. Per capita, production is about 1.5 to 2 litres per day containing about 11 g N and 1 g P. Thus opportunities still exist. Urinals in public toilets with high footfall (motorway service stations, stadia, etc.) could readily be adapted to collect significant volumes of urine at discrete locations, which then can be used locally to fertilise selected crops (eg energy crops) or for N and P recovery (eg struvite precipitation). Work is principally required to identify the social, economic, regulatory constraints on this potential market.

Growth of algal biomass within wastewater treatment works could be used to recover nutrients from wastewater. Energy can be recovered from the algae, and the residual biomass disposed to agricultural land. Research challenges are to understand algal growth kinetics so that processes can be engineered on large scales, energy optimisation (balancing energy use in algae production with energy recovery from the biomass), and ensuring that the resulting residues from the biomass after energy and P recovery can be used as a soil conditioner.

Phosphate can be strongly adsorbed by different inorganic materials. This research will study how sorption onto inorganic media can recover P from wastewater or from treated effluent so that it is not dispersed into the aquatic environment and lost. Further work will be required to understand solubilisation and mobilisation of these nutrients and heavy metal contaminants to understand how they behave. With this information, ways to return clean and safe resources to the land sustainably can be found.

Potential applications: With the correct processes in place, recovering water and key plant nutrients from waste streams and returning them to the farm in a safe and clean manner will help to reduce the release of excess nutrients to water systems and the atmosphere. This will extend the life of the planet's phosphate reserves by substituting recovered phosphate for virgin phosphate, secondly it will reduce algae bloom outbreaks in nearby aquatic systems (although progress is being made to bring these under control) and NOx emissions to the atmosphere. Awareness of the issue is increasing so there will be a market for effective, reliable technologies.

Potential non-academic partners: Agronomists, food suppliers and processors, supermarkets, water industry, regulatory agencies, (agro)chemical industry.

Project leads: Dr Tim Evans, Tim Evans Environment; Dr Doug Stewart, University of Leeds; Dr Charlie Shand, The James Hutton Institute; Prof Mark Tibbett, Cranfield University.

Project 3. Integrated models of plant-soil-water

Focus of project: Understanding the relationship between plants, soil and water is key in helping to develop and explore different models for agroecology and production in different environments. Many institutions are researching and understanding particular components of such systems at a laboratory and plot scale, although it is important to ensure that the data obtained at this level can be integrated between disciplines and is scalable to a field ecosystem or even, to global scale. Interdisciplinarity is essential. The knowledge exchange between soil and plant biology, physics and chemistry for process understanding, with agronomy, ecology, hydrology and geology to quantify impacts at landscape scale, and incorporation through mathematical modelling with methods from geospatial science and earth systems science, provides the basis for upscaling, potentially to planetary scale.

Proposed approach(es): Methods from plant and soil biology, physics and chemistry provide the integrated theoretical descriptions and measurements to describe the key coupling of processes from molecular- to cellular and soil grain scales, up to the scale of the soil profile. Comparing mathematical model results and measurements with data sets at landscape scale will show how model parameters and process rates vary spatially with plant and soil characteristics, plant cover and land use practice. Furthermore, this provides rules for aggregating process descriptions using geospatial data on soil, plant cover and land use at larger scales, from regional to global. This project proposal would initially require data obtained at a laboratory level and assess how the increase in physical size of the study system will affect the data collected and ensure that there is tractable methodology for up-scaling. Careful consideration of the tools to monitor these data and test mathematical descriptions at various scales would be needed. Procedures to monitor uncertainty and understand how we can predict these scenarios will be critical in the development of scalable models.

Research horizons: Computational simulation is a powerful tool to scope out alternative land use practices, crop systems, and agrochemical applications under different environmental scenarios . This methodology has the potential to move improvement of land use practice and agricultural production away from solely empirical approaches that employ plot and field trial methods, into a far more scientific analysis of field data, scoping predictions to design and help test new methods and practices. Building simulation tools is also a strongly integrating activity, forcing modelling teams to work with many different experts to conceptualise the problem in ways that account for a wide range of existing knowledge. Staged delivery of initially simple models that tackle a specific problem, such as simulating P cycling in a single field, help create a staged approach that achieves important, useful milestones at an early phase of R&D, and provide the platform for more complex simulation approaches as advances are achieved.

Potential applications: By collecting and understanding data at these varying levels there is scope to provide farmers with information on the impacts that certain models could have on their crops – for example extreme drought, leaching of nutrients from heavy rainfall etc. This would also be useful at higher levels of management, eg for government or local authorities to ensure that farmers are given support for an increase in insurance or poor water supplies in times of drought. The level of data collected will facilitate the translation of detailed soil maps of the UK, into indicators of soil quality, and also into parameters that allow analysis of land use impacts at national scale. It will also be useful for the Environment Agency to store and host a database of scenarios and information about the countryside surface. This could also contain meteorological and climatic data essential to industries when trying to define and understand the soil chemistry of the UK. Eventually, simulation methods could provide the quantitative scenario analysis to scope out the impact of new policy approaches, design precision agriculture approaches, test new agrichemical products, and assess risks of predicted environmental changes.

Potential non-academic partners: Land managers, agronomists, agriculture and environmental policy teams, agrichemical manufacturers, water utilities. An initial summary of key soil processes, their mathematical description and the relationship of model parameters to site-specific conditions would immediately provide an important resource for many professional scientists involved in land management decisions. Initial models at profile scale would provide an immediate tool to help analyse bench scale and plot studies of soil-plant-water interactions; for example, during commercial testing of soil treatments for specific plant strains. Field scale simulations would provide the basis for scoping operational changes to improve resource efficiency and more sustainable approaches to the production of specific crops.

Project lead at the OSCAR workshop: Prof. Steven Banwart, University of Sheffield.

Project 4. Nutrient / Water Use Efficiency

Project focus: This project will focus on the efficiency of phosphorus uptake into plants and its relationship to the uptake of water. It is essential that scientists understand the chemical mechanisms involved in the plant root cells at the molecular level, the binding and release energy required and also the effects of solid phase chemical speciation in buffering and supply of phosphorus around the intake zones of the root.

Proposed approach(es): There are many studies of the nitrogen and carbon cycle; a similar level of study for phosphorus is needed. To examine the phosphorus lifecycle, research is needed on plant uptake and releases via excretion and decay. How does phosphorus return to the soil and in what chemical form(s)? This knowledge is required at not only a natural environment level but also at a commercial farming level. As the population grows along with the demand on crops to feed this expansion, there will be a requirement to monitor phosphorus as a major factor in ensuring food security whilst also protecting water supplies.

Research horizons: Research will need to focus on the near root environment to enable us to examine the role of biosignalling in phosphorus uptake. The use of sensors and the latest micro-spectroscopic techniques will help quantify the concentration and chemical speciation of phosphorus in the ecosystem surrounding the root. The second stage should look at the plant's nutrient management systems in order to understand homeostasis and feedback mechanisms within plants.

Proposed applications: This will lead to the development of better fertiliser management and targeted nutrient application for crops; ie looking at specific nutrient and water applications that are both beneficial to the plant and the ecosystem. Such approaches will provide plants with the required amount of nutrients, whilst reducing the chances of runoff and over saturation of the other sites which bind phosphorus in the ecosystem.

Proposed non-academic partners and funding: We would anticipate that a number of research councils could be involved (NERC, BBSRC, EPSRC) in the basic research that focuses on the soil chemistry aspects. Access to large facilities such as Diamond Synchrotron would be by proposal. Agrochemical industries should be involved but all of them are now based offshore, particularly for research. HGCA should have a role in research and dissemination to farmers and consultants. This research is likely to impact though changes in practice and new products. These would also impact on legislation eg Defra/EU Water Framework Directive. In terms of sustainable phosphorus use, major supermarkets could have interest in sustainability and decreased environmental impact of food production systems. This research has international implications, and a number of bodies including DFID, FAO, CGAIRs and other organisations such as World Bank and charitable foundations may have interest in joining the programme at different stages.

Project leads at the OSCAR workshop: Prof. Steve McGrath, Rothamsted Institute.

Appendix 1

UK landscape for soils research, 2008 to present

A1. Royal Agricultural Society of England: 2008, 2010

In 2008 the Royal Agricultural Society 'Practice with Science' group published '*The Current Status of Soil & Water Management in England*', followed two years later by a report commissioned from Cranfield University entitled '*Gap Analysis on the Future Requirements of Soil and Water Management in England*'. These two reports champion soil as a vital resource that is being jointly neglected by government, the research community and farmers, and recommend a strategic initiative for soil research and development, jointly-owned by industry, the Research Councils and government, with input from other stakeholder groups.[47,48]

The report found that at present there appears to be a lack of the shared vision and governance needed to ensure soil research underpins future industry performance. Unless this problem is addressed there is a danger that the rationale for future soil research will not be appreciated and current funding will decline, leading to a lack of industry competitiveness as well as a strategic gap in UK capabilities.

A2. RSC Roadmap for the Chemical Sciences: 2009

The RSC produced its roadmap through a series of workshop and online consultations to identify priority areas and opportunities for chemistry to drive both UK and international science agendas through to 2020. Food and agricultural productivity were key themes. The report states:

The world faces a food crisis relating to the sustainability of global food supply and its security. The strain on food supply comes primarily from population growth and rising prosperity, which also bring competing land and energy demands. By 2030 the world's population will have increased by 1.7 billion to over eight billion.[49] Climate volatility and the declining availability of water for agriculture will greatly increase the challenges facing farmers.

To match energy and food demand with limited natural resources, without permanently damaging the environment, is the greatest technology challenge humanity faces. The application of chemistry and engineering is a key part of the solution.[50]

Maintaining good soil structure and fertility are important to ensure high productivity. It is therefore necessary to understand the complex macro-and micro-structural, chemical and microbiological composition of soil and its interactions with plant roots and the environment. This should also include an understanding of the mechanical properties of soils and the flow of nutrients.

A lack of information on agroecology is a major barrier to the adoption of sustainable agricultural practices worldwide. Research should be carried out to improve the understanding of the biochemistry of soil systems. Specific examples include the chemistry of nitrous oxide emissions from soil and the mobility of chemicals within soil. Additionally, improved understanding of methane oxidation by soil methanotrophic bacteria would help in developing methane-fixing technologies. There is also scope for optimising how fertilisers are used. Fertilisers should be formulated to improve soil nitrogen retention and uptake by plants. Furthermore, low energy synthesis of nitrogen and phosphorus-containing fertilisers would increase the sustainability of agricultural production by reducing indirect input costs and resource requirements.[51]

Chemical science will play a pivotal role in developing rapid in situ biosensors systems and other chemical sensing technologies. These sensors can be used to monitor a wide range of parameters, including soil quality and nutrients, crop ripening, crop diseases and pests, and water availability. This will allow farmers to pinpoint nutrient deficiencies, target agrochemical applications and improve the quality and yield of crops.

Tracking and understanding the impact of climate change parameters will facilitate the development of predictive climatic models, thus identifying changing conditions for agronomy and providing valuable data for the planting and targeted treatment of crops.

Improved engineering tools will result in greater efficiencies in on-farm practices such as grain drying, seed treatment and crop handling and storage.

A3. UK Government Office for Science: 2010, 2011

Two recent landmark reports published by the UK Government Office for Science are of particular relevance to those interested in soils. The Foresight report *Land Use Futures*[52] highlighted the requirement to maintain high quality land resources not only for agriculture but also for non-priced 'public goods' such as flood risk management, biodiversity and carbon sequestration, putting farmers and land managers under increasing pressure to protect soils at the same time as increasing overall production in response to the challenges of global food security.

The subsequent Foresight report *The Future of Food and Farming* argues the need for more fundamental research:

Food security in 2030 and out to 2050 will require new knowledge and technology, and the basic and applied research underlying this needs to be funded now; there is evidence of a slowdown in productivity gains today correlated with a reduction in research and development (R&D) investment in many countries over the last two decades.[53]

This report identifies specific requirements for R&D in order to meet the challenge of producing food more sustainably. These include:

Scientific and technological advances in soil science and related fields. Relatively neglected in recent years, these offer the prospect for a better understanding of constraints to crop production and better management of soils to preserve their ecosystem functions, improve and stabilise output, reduce pollutant run-off and cut greenhouse gas emissions.

The report goes on to draw attention to 'the risk of negative irreversible events if action is not taken; this includes the loss of biodiversity, the collapse of fisheries and the loss of some ecosystem services (for example the destruction of soils).'

A4. UK National Ecosystem Assessment: 2011

The UK National Ecosystem Assessment (2011) has raised awareness across government (and beyond) of the importance of the various ecosystem services provided by soils, particularly the supporting and regulating services (eg nutrient cycling) that underpin the more widely understood (and measured) provisioning services (eg crop production).

Chapters 13 and 14 of the Assessment highlight not only the value of these frequently unrecognised services but also the degree of uncertainty surrounding our understanding of the mechanisms involved, and the need for better data to support more robust evaluation of them.[54]

A5. Environmental Sustainability KTN Soil Health and Sustainability: 2011

In 2011 NERC commissioned the ESKTN to carry out a consultation on soil health and sustainability with a broad cross section of stakeholder organisations who were concerned directly or indirectly with soils and the services supplied by the soil ecosystem.[55] The views of a variety of industry, retail and third sector organisations were incorporated with those of the research and policy communities in developing a road map of research challenges, articulating research requirements and priorities as perceived by more than 50 different stakeholders who participated in the consultation and associated workshop.

The results of this work showed that there is a considerable potential for greater collaboration and integration of research activities from the various funders outside the research councils, as well as between different research councils for funding soil health and sustainability research. There is also scope for greater synergy with projects taking place within the EU and beyond.

Some of the key research priorities identified in the report include:

- Better understanding of soil biodiversity and functions related to land management practices.
- Establishing and maintaining long-term trials and demonstration plots.
- Integrated studies of nutrient fluxes from field measurements to modelling and more integrated plant and soil system approaches and models.
- The potential for using data mining on existing global research outputs.
- Development and use of sensors in order to provide adequate field measurements and assessments of variability.

A clear message also emerged of the need for improved mechanisms to facilitate sharing the results of publicly-funded research more widely among different user groups, such as the levy bodies and other representative organisations.

There are opportunities to be much more creative and effective in knowledge exchange and dialogue at many different levels, which would be facilitated by increased funding and greater emphasis on KE, coupled with dissemination through more demonstration projects.

A6. Natural Environment White Paper: 2011

The 2011 Natural Environment White Paper, *The Natural Choice: securing the value of nature*, sets out the government's intention to enhance the environment, economic growth and personal wellbeing and to restore nature's systems and capacities. Chapter 2 includes a specific section, 'Safeguarding our soils', which explicitly recognises the range of important ecosystem services and functions delivered by soils. It also puts the cost to the economy of soil degradation at more than £150-250 million per year and recognises that while soil degradation is often very rapid, recovery and restoration of soil health is difficult and lengthy.

Section 2.61 of the paper states:

By 2030 we want all of England's soils to be managed sustainably and degradation threats tackled successfully, in order to improve the quality of soils and to safeguard their ability to provide essential ecosystem services and functions for future generations.

It goes on to make the following commitment:

We will undertake a significant research programme over the next four years to explore how soil degradation can affect the soil's ability to support vital ecosystem services such as flood mitigation, carbon storage and nutrient cycling; and how best to manage our lowland peatlands in a way that supports efforts to tackle climate change. We will use the results of this research to set the direction of future action.

However, there is currently no specific soil strategy for England, the current government having not adopted *Safeguarding our Soils*, the first soil strategy for England, published in September 2009.[56] That strategy included six priority areas:

- Better protection for agricultural soils
- Protecting and enhancing stores of soil carbon
- Building the resilience of soils to climate change
- Preventing soil pollution
- Dealing with the legacy of contaminated land
- Ensuring effective protection of soils during development and construction

There was also specific reference in the 2009 strategy to needing:

More evidence on the ecosystem services that soils provide for society, the value of these services, assessments of the pressures soils face, how resilient service delivery might be to these pressures and the means to manage continued delivery of these services.

A7. The State of Soil in Europe: 2012

Finally, the recently published JRC report The State of Soil in Europe points out that these are common problems across the rest of Europe with soil resources being over-exploited, degraded and irreversibly lost. The report calls for:

'…initiatives to raise awareness in society as a whole of the value and importance of soil…', as well as '…understanding the economic, social and environmental benefits of soil functions and the impact of degradation processes over time…' [57]

Appendix 2

OSCAR workshop programme

Day 1 – Monday 28 November 2011

THEME – State of the science, demands of policy, challenges for industry

Arrival and refreshments
Introduction Dr David Lawrence
Plenaries - State of the Science I Professor Steven Banwart, *Sheffield*, Dr Jonathan Leake, *Sheffield*, Professor Liane Benning, *Leeds*
Plenaries - State of the Science II Professor Guy Kirk, *Cranfield*, Elizabeth Baggs, *Aberdeen*
Plenary – The UK Industry Perspective Dr Ray Elliott, *Syngenta R&D*, Dr Kevin Moran, *Yara*
Breakout Group Discussions I Key challenges in soil science
Plenary – The UK Policy Landscape Professor Robert Watson, *Defra*

Day 2 – Tuesday 29 November 2011

THEME - Optimising soil systems: overcoming soil and resource limitations on agriculture intensification

Arrival and refreshments
Briefing on Day 1 outcomes Dr Ray Elliott, *Syngenta*
Plenary – Resource Sustainability Dr Albino Maggio, *EC Directorate General-Joint Research Centre*, Dr Richard Miller, *Technology Strategy Board*, Dr Callum Murray, *Technology Strategy Board*
Breakout Group Discussions II Key challenges in resource sustainability
Plenary – Solutions from Chemistry Professor Peter Dobson, *Begbrook Science Park*, Dr Gareth Wakefield, *Oxford Advanced Surfaces*
Breakout Group Discussions II Identifying solutions in chemical science – projects, partnerships, leaders
Plenary Discussion Co-ordinating the response

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