The top 100 questions of importance to the future of global agriculture

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Despite a significant growth in food production over the past half-century, one of the most important challenges facing society today is how to feed an expected population of some nine billion by the middle of the 20th century. To meet the expected demand for food without significant increases in prices, it has been estimated that we need to produce 70–100 per cent more food, in light of the growing impacts of climate change, concerns over energy security, regional dietary shifts and the Millennium Development target of halving world poverty and hunger by 2015. The goal for the agricultural sector is no longer simply to maximize productivity, but to optimize across a far more complex landscape of production, rural development, environmental, social justice and food consumption outcomes. However, there remain significant challenges to developing national and international policies that support the wide emergence of more sustainable forms of land use and efficient agricultural production. The lack of information flow between scientists, practitioners and policy makers is known to exacerbate the difficulties, despite increased emphasis upon evidence-based policy. In this paper, we seek to improve dialogue and understanding between agricultural research and policy by identifying the 100 most important questions for global agriculture. These have been compiled using a horizon-scanning approach with leading experts and representatives of major agricultural organizations worldwide. The aim is to use sound scientific evidence to inform decision making and guide policy makers in the future direction of agricultural research priorities and policy support. If addressed, we anticipate that these questions will have a significant impact on global agricultural practices worldwide, while improving the synergy between agricultural policy, practice and research. This research forms part of the UK Government's Foresight Global Food and Farming Futures project.

Keywords: Farming; food security; global agriculture; horizon scanning; policy; research questions

Introduction

Despite a significant growth in food production over the past half-century, one of the most important challenges facing society today is how to feed an expected population of some nine billion by the middle of the 20th century. To meet the expected demand for food without significant increases in prices, it has been estimated that we need to produce 70–100 per cent more food, in light of the growing impacts of climate change and concerns over energy security (FAO, 2009a; Godfray *et al.*, 2010). It will also require finding new ways to remedy inequalities in access to food. Today the world produces sufficient food to feed its population, but there remain more than one billion people who suffer from food insecurity and malnutrition (IAASTD, 2009). This challenge is amplified further by increased purchasing power and dietary shifts in many parts of the globe, barriers to food access and distribution, particularly in the poorest regions, and pressure to meet the Millennium Development Goal of halving world poverty and

hunger by 2015 (World Bank, 2007; Pretty, 2008; IAASTD, 2009; Royal Society, 2009). Despite the emergence of many innovations and technological advances in recent decades, this combination of drivers poses novel and complex challenges for global agriculture, which is under pressure to ensure food and energy security in ways that are environmentally and socially sustainable (National Research Council, 2010a). Complicating matters further, the past half-decade has seen a growing volatility of food prices with severe impacts for the world's poor, most notably during the food price peaks of 2007–2008 (von Braun, 2010), and political and scientific controversy over the role that biofuels play (FAO, 2008; Fargione *et al.*, 2008; Searchinger *et al.*, 2008) in affecting carbon sinks and emissions. Indeed, land-use change (for any purpose) is already implicated as a major driver of global change (Tilman *et al.*, 2001; InterAcademy Council, 2004; Rockstrom *et al.*, 2009; Harvey and Pilgrim, 2010). Agricultural and food systems are estimated to account for one-third of global greenhouse gas emissions, more than twice that of the transport sector (IPCC, 2007; Harvey and Pilgrim, 2010). Thus the goal of the agricultural sector is no longer simply to maximize productivity, but to optimize it across a far more complex landscape of production, rural development, environmental and social justice outcomes (IAASTD, 2009; Godfray *et al.*, 2010; Sachs *et al.*, 2010).

The complexity of drivers facing global agriculture has recently received growing recognition (World Bank, 2007; Royal Society, 2009; National Research Council, 2010a). However, there remain significant challenges to developing national and international policies that support the wider emergence of more sustainable forms of land use and efficient agricultural production across both industrialized and developing countries (Pretty, 2008). The complexity, and often lack, of information flow between scientists, practitioners and policy makers is known to exacerbate the difficulties, despite increased emphasis upon evidence-based policy (Defra, 2003; Sutherland *et al.*, 2004, 2010b; Haddad *et al.*, 2009). In this paper, we seek to improve dialogue and understanding between agricultural research and policy by identifying 100 of the most important questions for global agriculture. These have been compiled by leading experts and representatives of major agricultural organizations across the world, and the aim is to use sound scientific evidence to inform decision making and guide policy makers in the future direction of agricultural research priorities and policy support. Just as it is imperative to ensure that policy decisions are informed by scientific knowledge and priorities, it is also vital that research should be directed at issues that influence current and future policy frameworks and be relevant to the needs and issues of farmers and agriculturalists in different parts of the world, enabling public science and policy institutions to become proactive rather than reactive (Pretty, 2009). It is also important to note that the solutions to agricultural problems are likely to be context and culture specific while the following 100 questions are generic and context neutral.

The horizon-scanning approach used here has been employed previously to identify questions of greatest relevance to policy makers, practitioners and academic researchers in the fields of ecology and conservation (Sutherland *et al.*, 2006, 2009). The latter was based on consultations with representatives from the world's major conservation organizations, professional scientific societies and universities. It targeted researchers who wanted to make their work more applicable to the practices of conservation and organizations wishing to review and direct their research and funding programmes. The former was based on consultations with representatives from 37 UK organizations, including government, non-government organizations (NGOs) and academia. In this case, the questions were selected by policy makers and practitioners and the target audience was the academic community. Since 2006, a number of similar collaborative exercises have been conducted in the UK, the USA and Canada to identify priority research questions, opportunities for developing new policies and emerging issues in conservation (Sutherland *et al.*, 2008, 2009, 2010a).

Our objective was to compile a list of the top 100 questions that, if addressed, would have a significant impact on global agricultural practices worldwide, while improving the synergy between agricultural policy, practice and research. In order to meet this objective, we employed a collaborative and inclusive horizon-scanning approach designed to maximize openness to different perspectives, democracy in consolidating these perspectives, and scientific rigour (Sutherland *et al.*, 2010b). We gathered a team of senior representatives and experts from the world's major agricultural organizations, professional scientific societies, non-government and academic institutions, which are linked in various ways to the potential beneficiaries of this research, including farmers and policy makers. The intention is that the

list of questions thus devised will guide policy support and priorities for agricultural research programmes in the coming years. Therefore, our intended audiences include policy makers involved in directing future agricultural policy and research, and researchers looking to direct and prioritize their own efforts and programmes of work. The questions fell into a number of areas or themes that were identified as a priority for future agricultural research. This paper reports on the final list of questions that emerged and discusses each group of questions by placing them within the context of current agricultural issues. This research forms part of the UK Government's Foresight project on Global Food and Farming Futures.

Methods

A multi-disciplinary team of senior representatives and experts from the world's major agricultural organizations, professional scientific societies and academic institutions was selected to form a Core Group of experts to identify the top 100 questions for global agriculture and food. This resulted in 45 institutions being contacted from countries across the world. Although the headquarters of many international institutions were based in Western Europe or North America, most of the representatives have extensive agricultural experience outside those regions since these entities have international or global mandates. Invitations were sent that outlined the procedure and responsibilities of Core Group members. The final Core Group comprised 55 senior representatives based in 21 countries. The list of authors in the author group provides details of individuals and their participating institutions.

The list of 100 questions was arrived at through a three-stage process. Initially, all Core Group members were asked to canvas their professional networks and consult widely among their colleagues in order to submit a list of priority questions. Core Group members were encouraged to think widely and consult with those outside of their particular expertise (Sutherland *et al.*, 2010b). A number of approaches were employed to solicit questions, including convening workshops, seminars, discussions groups and circulating e-mails, in which other members of the institution could nominate questions answerable by research, but for which substantial knowledge does not already exist. Questions had to fill a number of criteria: (i) they had to be answerable and capable of a realistic research design; (ii) they had to be capable of a factual answer and not dependent on value judgements; (iii) they had to be questions that have not already been answered; (iv) questions on impact and interventions should have a subject, an intervention and a measurable outcome; (v) questions for which yes or no are likely answers were unsuitable; and (vi) questions should be of the scale that in theory a team might have a reasonable attempt at answering. An ideal question suggests the design of research that is required to answer it or can be envisioned as translating the question into discrete and more directly testable research hypotheses (Pullin *et al.*, 2009). A total of 618 formalized questions (along with the name and organization of the person who suggested the question) were submitted for consideration.

The submitted questions were sorted into 14 themes relating to agricultural priorities: (a) climate, watersheds, water resources and aquatic ecosystems; (b) soil nutrition, erosion and use of fertilizer; (c) biodiversity, ecosystem services and conservation; (d) energy, climate change and resilience; (e) crop production systems and technologies; (f) crop genetic improvement; (g) pest and disease management; (h) livestock; (i) social capital, gender and extension; (j) development and livelihoods; (k) governance, economic investment, power and policy making; (l) food supply chains; (m) prices, markets and trade; (n) consumption patterns and health. The Core Group was then divided into 14 Expert Groups (comprising 3–5 experts), each led by one coordinator, responsible for introducing and developing a designated theme. Core Group members were invited to join as many Expert Groups as they wished; no limits were put on group size. The task of the Expert Groups was to review the unabridged questions (authors' names and affiliations were removed at this point to reduce potential bias) in their allocated theme, revise, recombine or reword them where relevant to ensure clarity and lack of repetition, add new questions where there are gaps, and then sort them into five 'Essential' questions, and around 10 'Possible' questions (the latter was flexible and left to the discretion of each group). Essential questions were defined as those questions that, if answered, would have the greatest impact on global agriculture and food systems worldwide. The remaining questions were rejected. Ranking of questions was avoided as this was perceived to increase the pressure to create broad questions (Sutherland *et al.*, 2010b). To enhance participation and transparency, all 14

groups of questions were circulated to Core Group members electronically. This gave each participant the opportunity to refine and develop questions in any theme as they saw fit. This culminated in a list of 70 Essential and 146 Possible questions spread across the 14 themes.

In the final stage, the 70 Essential questions identified by the Expert Groups automatically qualified for inclusion in the final 100. The other 30 questions were selected from the 146 Possible questions through an electronic voting process mediated by a secretariat. Each Core Group member was given a maximum of 30 votes; these could be allocated to the Possible questions of their choice. Core Group members were asked to review and vote on the full list of Possible questions, not just the questions relevant to their theme. In total, 1385 votes were cast. At all stages, Core Group members were invited to revise and rephrase questions where they felt it relevant. The data were then compiled, the total scores for each question were calculated, and the 30 questions with the most votes were selected for inclusion in the final 100. The final list of 100 questions was then circulated to all Core Group members for a final round of editing.

Results

We have organized the 100 questions into four overarching sections that reflect stages of the agricultural production system: (i) natural resource inputs; (ii) agronomic practice; (iii) agricultural development; and (iv) markets and consumption. There is some overlap between different themes, for instance concerns about crop genetic improvement often relate to biodiversity conservation, or questions about livestock refer to climate change, but we have ensured that there is no repetition in the final list. The final 100 questions are not ranked in order of priority.

Section 1: Natural resource inputs

Climate, watersheds, water resources and aquatic ecosystems

Climate change predictions point to a warmer world within the next 50 years, yet the impact of rising temperatures on rainfall distribution patterns in much of the world remains far less certain (IPCC, 2007). The situation for oceans is equally serious, with coastal ocean temperatures documented to be warming 3–5 times more rapidly than the projections of the Intergovernmental Panel on Climate Change, and the capacity of marine ecosystems to sequester one-half of global carbon becoming impaired (Henson, 2008). From a global food security perspective, many commercial fish species are becoming economically extinct, with recent surveys showing 63 per cent of fish stocks globally needing intensive management towards rebuilding biomass and diversity due to exploitation (FAO, 2005).

Interventions are required across scales, from small fields to communities, watersheds, catchments and ultimately whole river basins, with a focus on increasing the productivity of both ‘green’ and ‘blue’ water use (Humphreys *et al.*, 2008). In some countries, 85 per cent of diverted water resources are now directed into agriculture with increasing competition for urban and industrial usage. For this reason, the need for improved crop, soil and water management practices, particularly in light of climate change, is growing.

1. What are the predicted critical impacts of climate change (e.g. changes in temperature, wind speed, humidity and water availability, storm intensity, crop water requirements, snowmelt and seasonal runoff, pests, waterlogging, agroecosystem shifts, human migration) on agricultural yields, cropping practices, crop disease spread, disease resistance and irrigation development?
2. What would be the global cost of capping agricultural water withdrawals if environmental reserves were to be maintained?
3. What is the effect of increased rainwater harvesting on local hydrological fluxes, and how do local changes combine and alter water resource availability at larger geographic scales?
4. How can aquaculture and open water farming be developed so that impacts on wild fish stocks and coastal and aquatic habitats are minimized?
5. What approaches (operational, agronomic, genetic, supplemental irrigation schemes, fertility management, winter rainfall storage) can be developed to increase water use efficiency in agriculture and what is the cost-effectiveness of these approaches?
6. What combinations of forestry, agroforestry, grass cover, water-collecting systems and storage facilities, drought-resistant crops and water-saving technology are needed in arid and semi-arid areas to increase food production, and to what extent can they become cost-effective?

7. How can the allocation of water be optimized between irrigated agriculture and environmental functions, and what innovative policies and technologies can minimize trade-offs between irrigation and healthy functions of natural ecosystems?

Soil nutrition, erosion and use of fertilizer

The management of soil fertility is essential to enhancing and sustaining agronomic and biomass productivity. Nutrients harvested in crops (i.e. grains, roots and tubers, stover, fruits, timber) need to be replaced in order to ensure that the innate nutrient capital of the soil is not eroded. Intensively managed agroecosystems are only sustainable in the long term if the outputs of all components produced are balanced by appropriate inputs. Whether the required amount of plant nutrients to obtain the desired yield is supplied through organic (biofertilizers) or inorganic (synthetic chemicals) means is a matter of logistics, availability, prices, environmental impacts and the scale at which nutrient sources and sinks are assessed. Plants do not differentiate the nutrients supplied through organic or inorganic sources. An important issue is that of nutrient availability, in sufficient quantity, in appropriate forms, and at the phenological stage when nutrient availability is critical for optimum growth and yields. For an equivalent amount of nutrients required, supplying through manure, compost and other biofertilizers has positive impacts on soil physical, chemical and biological quality. However, the bulk amount (5–10Mg/ha/year) required for 1.5 billion hectares of cropland poses logistical questions of availability, transport and application.

Excessive removal of fertile surface soil by water and wind erosion is an important form of soil degradation and leads to desertification. As soil organic matter and plant nutrients are concentrated in surface soils, these materials along with the clay fraction are removed preferentially. In addition to the loss of nutrient reserves and the decrease in effective rooting depth, loss of water as runoff and long-term reduction in available water capacity also adversely impact crop growth and yield. Soil degradation by the depletion of nutrients and soil organic carbon pools, exacerbated by a perpetual use of extractive farming practices, is a major issue in developing countries of sub-Saharan Africa, south and South East Asia and the Caribbean.

8. What benefits can sustainable soil management deliver for both agricultural production and delivery of other ecosystem services?
9. What are the best uses of organic amendments by subsistence farmers in cropping systems to improve soil nutrients and water-holding capacities and thereby assist in restoring agroecosystems?
10. What are the most practical and economic methods for managing soil fertility in paddy soils and upland production systems in the tropics?
11. What guidelines can be established for poor small-scale farmers to ensure that nitrogen fertilization is managed in a way that results in net accretion of soil organic carbon rather than net mineralization?
12. How can salinization be prevented and remedied?
13. How can native soil organisms be exploited to maximize food productivity and minimize environmental impacts?
14. What are the world's mobilizable stocks and reserves of phosphate, and are they sufficient to support adequate levels of food production globally for the next century?

Biodiversity, ecosystem services and conservation

Agriculture has been a leading cause of loss of global biodiversity due to conversion of natural habitats, such as forests and wetlands, into farmland (Green *et al.*, 2005). Furthermore, the increased efficiency of agriculture has resulted in dramatic declines of many species using farmland habitat. Key drivers include the increased use of synthetic pesticides, herbicides and fertilizers, increased landscape homogeneity due to regional and farm-level specialization, drainage of water logged fields, loss of marginal and uncropped habitat patches, and reduction of fallow periods within arable rotations (Robinson and Sutherland, 2002; Benton *et al.*, 2003; Wilson *et al.*, 2009). Moreover, the intensification of agriculture has been central to the degradation of ecosystem services, and has both increased the production of greenhouse gases and the reduced levels of carbon sequestration (UNEP, 2010).

The major challenge is to understand the best compromises between increasing food production while minimizing the negative impacts on biodiversity, ecosystem services and society. Increased global food production must come from some combination of increased production on land already farmed or an increase in farm area. Furthermore, new technologies will provide a means of increasing both the intensity of agriculture and the areas suitable for agriculture,

for example through drought-resistant crops. Determining the best compromise requires an improved understanding of how to use new technologies, agri-environment schemes and the balance of intensification and extensification to ensure sustainable food production, ecosystems services, biodiversity and socioeconomic impacts.

15. What is the relationship between productivity and biodiversity (and/or other ecosystem services) and how does this vary between agricultural systems and as a function of the spatial scale at which land is devoted mostly to food production?
16. How should the options of intensification, extensification, habitat restoration or the status quo be chosen and how can we best combine measures of economic, environmental and social benefit to make the choice?
17. What are the environmental consequences of drought-resistant crops in different locations?
18. What are the consequences for biodiversity conservation and delivery of other ecosystem services if crop and livestock management is driven by the objectives of greenhouse gas emission reduction?
19. In intensive production systems, are agri-environment measures best deployed to buffer protected areas and areas of pristine or semi-natural habitat, or to ‘soften the matrix’ between patches of these habitats?
20. Where would natural habitat restoration provide the greatest food and environmental benefits to society?
21. What type and specific combinations of improved technologies, farming practices, institutions and policies will result in the maintenance of ecosystem services, including soil fertility, in agricultural systems undergoing intensification in developing countries, in particular in sub-Saharan Africa?
22. Can payments for ecosystem services (e.g. carbon sequestration, green water credits, biodiversity enrichment) lead to adoption of recommended land-use and management practices by resource-poor farmers in developing countries?

Energy, climate change and resilience

As demand for energy grows in the coming decades, alternative energy sources will need to be identified to sustain the growing global population. Agriculture uses a considerable amount of energy, both directly in machinery, and embedded within products used in agriculture (Schneider and Smith, 2009). The effects of high oil prices on low-income rural households, and globally on agricultural inputs (pesticides and nitrogen fertilizers), transport, tillage and irrigation systems, could produce declines in agricultural productivity, thus exacerbating the pressures to expand the area of cultivated land at lower levels of productivity (Harvey and Pilgrim, 2010).

Climate change is now one of the greatest challenges facing humanity, and it will impact agriculture in many ways, some positive and some negative. The already significant challenge of producing more food using fewer inputs is exacerbated by the need for agriculture to adapt to climate change, while also reducing greenhouse gas emissions arising from agriculture in order to mitigate climate change (Smith and Olesen, 2010). Resilience to climate change will need to be a key property of sustainable agricultural systems in the coming decades, particularly in those regions projected to experience severe ecological shifts due to a changing climate.

23. What are the best options for agriculture increasing food production while simultaneously reducing its contribution to greenhouse gas emissions?
24. What will be the risk of mass migration arising from adverse climate change, and how will this impact on agricultural systems?
25. Given the high current direct and indirect energy inputs into agriculture, how can food production be made carbon neutral to allow emission targets to be met over the next 40 years?
26. How would different market mechanisms of payment for greenhouse gas reduction and carbon storage in agriculture affect farming and how could these best be implemented?
27. How can competing demands on land for production of food and energy best be balanced to ensure the provision of ecosystem services while maintaining adequate yields and prices?
28. How can the resilience of agricultural systems be improved to both gradual climate change and increased climatic variability and extremes?
29. What is the appropriate mix of intensification and extensification required to deliver increased production, greenhouse gas reduction and increased ecosystem services?
30. How can crop breeding, new technologies, the use of traditional crops and improved agronomic

practice be balanced to increase food production and enhance resilience to future climate change?
31. How can the transition from a hydrocarbon-based economy to a carbohydrate-based economy best be made using biorefineries to process agricultural products to provide high-value products, biomaterials, energy and soil improvers, in addition to the food products currently produced?
32. How can long-term carbon sinks best be created on farms (e.g. by soil management practices, perennial crops, trees, ponds, biochar)?
33. How can the inclusion of agriculture in carbon markets provide significant benefits for farmers?

Section 2: Agronomic practice

Crop production systems and technologies

Crop production will have to increase by 70–100 per cent to meet growing food and feed demand driven by human population growth and likely increases in income generation during the 21st century (FAO, 2009a; Godfray *et al.*, 2010). Moreover, because of limits on land and water resources, a significant increase in production must come through acceleration of the rate of technological change to propel the sustainable intensification of crop and livestock production systems (World Bank, 2007; FAO, 2009b; Royal Society, 2009; Godfray *et al.*, 2010; National Research Council, 2010a).

The contending paradigms that have tended to divide strategies based on agricultural biotechnology and organic systems have only begun to receive the scientific attention they deserve (Royal Society, 2009; National Research Council, 2010b). There is, for example, often a lack of consensus on the coexistence of organic agriculture and genetically modified (GM) technologies. An emerging discourse suggests that what is needed is not a single path but many paths of sustainable intensification based on a wide variety of systems (from fallow rotation, agroforestry, mixed crop-livestock and crop aquaculture systems to minimum tillage and precision agriculture) that are appropriate to a large number of specific agroecological and socioeconomic contexts. It will be increasingly important to understand how science-based efforts can respond to real challenges and produce results useful to sustainable intensification that fit a diversity of circumstances.

34. What are the benefits and risks of embracing the different types of agricultural biotechnology (environmental impacts; sensitivity/resistance to environmental stressors such as heat, drought, salinity; dependence on/independence from inputs; risks of accelerated resistance; food safety, human health and nutrition; economic, social and cultural impacts)?
35. What are the advantages and disadvantages of organic production systems in terms of biodiversity, ecosystem services, yield and human health, particularly in resource-poor developing countries?
36. What practical measures are needed to lower the ideological barriers between organic and GM, and thus fully exploit the combined potential of both GM crops and organic modes of production in order to achieve agroecological management practices compatible with the sustainable intensification of food production?
37. What is the long-term capacity of fossil fuels and nitrogen, phosphorus and potassium fertilizer stocks to support intensive production systems globally?
38. How can food production systems that reduce dependence on externally derived nitrogen, phosphorus and potassium resources be designed?
39. How can we develop agreed metrics to monitor progress towards sustainability in different agricultural systems that are appropriate for, and acceptable to, different agroecological, social, economic and political contexts?
40. What part can reclamation, restoration and rehabilitation of degraded land play in increasing global food production?
41. What are the best integrated cropping and mixed system options (including fallow rotations and other indigenous cropping systems for cereals, tubers and other staples, agroforestry, crop-livestock and crop-aquaculture systems) for different agroecological and socioeconomic situations, taking account of climate and market risk, farm household assets and farmers' circumstances?

Crop genetic improvement

Since the earliest domestication of crops for food, fibre and fodder some 10,000 years ago, humans have been beneficially exploiting through selection the wide genetic diversity that is readily encountered in most crop species and their close relatives (Hancock, 2005). However, it was only at the turn of the 20th century that scientifically based crop breeding commenced (Biffin, 1905). Over the past

century, improvements in the yield and quality of the limited number of crop species on which humans now depend have been remarkable. For example, yields of maize, rice and wheat in China are 36, 25 and 60 per cent higher, respectively, now than they were 20 years ago (FAO, 2009c). For the first five decades after the turn of the last century, advances were made almost exclusively by hybridization (including inter-specific hybridization) followed by selection. Subsequently, a range of technologies, including tissue culture, mutagenesis, genetic transformation and a range of marker-aided selection methodologies, have enabled greater genetic diversity to be explored, created and exploited with increased efficiency (Allard, 1999). The green revolution of the 1960s was founded on the selection of wheat and rice types with a semi-dwarf habit that enabled yields to double (Ruttan, 1977; Khush, 1999). In other crops such as maize and many vegetables, the advent of genetic technology enabled hybrid vigour and crop uniformity to be exploited with a huge impact on productivity (Allard, 1999; George, 2009).

However, despite the enormous contribution that plant breeding has made to the elevation of crop yield and quality in agriculture, there are some crops and geographical regions or cropping environments where less effort has been expended. There are also biophysical limits to yield potential (Gressel, 2010). At the same time, increased emphasis on the need for improved resource use efficiency (water, energy, nutrients) in crop production systems coupled with reduced greenhouse gas emissions has begun to alter the priorities for the traits to be targeted in genetic improvement programmes (Khush, 1999; Tilman *et al.*, 2002). Nutritional crop quality for livestock and humans is also assuming a higher priority (Bouis, 1996). Moreover, public, private and philanthropic investment in crop genetic improvement has, over the last two decades, been both stimulated and constrained by issues related to the protection of intellectual property (Blakeney, 2009) and regulation of technology (Gressel, 2008). This particularly relates to the patenting and restricted licensing of genes and advanced technologies that facilitate gene identification, gene transfer or targeted mutagenesis, as well as the regulatory frameworks that have been developed to assess and respond to perceived risks.

42. What are the gains in resource use efficiency that could be achieved by crop genetic improvement for resistance to abiotic and biotic stresses?
43. What improvements to crop varieties can be made to ensure that emissions of greenhouse gases from agriculture and horticulture are significantly reduced?
44. What is the comparative effectiveness of different genetic approaches to the development of crops with tolerance of abiotic stresses such as frost, heat, drought, waterlogging, acid infertility and salinity?
45. What is the efficiency of different ways to genetically improve the nutrient-use efficiency of crops and simultaneously increase yield?
46. What impact can crop genetic improvement have on levels of micronutrients available to humans, livestock and fish?

Pest and disease management

New pests and diseases continue to damage crop yields and catch farmers and agriculturalists unaware. The history of pest research is dominated by these catastrophes, demanding emergency research. New problems will emerge in the future, and perhaps even more urgently, as climate change alters pest–crop relations in unforeseeable ways.

Substantial progress has been made over the decades since the 1960s in developing Integrated Pest Management (IPM). From its beginnings with classical biological control and host-plant resistance, to more recent efforts at targeted plant species diversification methods, such as 'push–pull' techniques (Hassanali *et al.*, 2008) and other landscape management methods for enhanced biological control, IPM has been fundamentally an agroecological approach to pest and disease management. Nevertheless, despite its successes and multiple benefits to farmers and to society, research and application of IPM methods is lagging (National Research Council, 2010a).

However, pest research has tended to be dominated by an insect bias, with diseases in second place and weeds third. Research needs to broaden to study causal organisms in proportion to the damage they cause. Recent donor-driven and academic pest management research has focused on IPM techniques, with a bias towards alternatives to chemical control. Meanwhile industry has contributed to research on new technologies, for example, pest-resistant genetically modified organisms, and pesticides that are lethal to insects but less toxic to vertebrates (e.g. chitin growth inhibitors). Meaningful engagement is needed between these sectors in the future. Pest and disease management can contribute to

increased food production, but only by developing a new generation of technology that controls the heavy crop and post-harvest losses caused by bugs, birds, weeds and microorganisms. In this way, effective pest and disease management can help reduce poverty and hunger. The added threat of global climate change clearly makes even more imperative the need for both adaptive management and rapid innovation to address future threats to agricultural development.

47. What evidence exists to indicate that climate change will change pest and disease incidence?
48. How can insecticide application in agriculture be modified to lessen the evolution of pesticide resistance in mosquitoes and other major vectors of human disease?
49. How can landscape-level interventions help pest management and which approaches are the most economically and socially sustainable?
50. How can perennial-based farming systems include cover crops as a pest management method and what are the economic and non-economic costs and benefits?
51. How can intensive livestock systems be designed to minimize the spread of infectious diseases among animals and the risk of the emergence of new diseases infecting humans?
52. How can increasing both crop and non-crop biodiversity help in pest and disease management?

Livestock

Livestock provide a valuable source of food (CAST, 2001) and play important agricultural and cultural roles in societies worldwide (Sansoucy, 1995; Schiere *et al.*, 2002; FAO, 2009d). The livestock sector supports almost one billion of the world's poorest people, often in combination with cropping. With livestock constituting the world's largest user of land resources (80 per cent of all agricultural land is under grazing or feed crops) and 8 per cent of global water use, the sustainability of livestock production systems is increasingly being addressed (Steinfeld *et al.*, 2006).

The livestock sector faces many challenges, such as the need to adapt to changing climates, which will provide more favourable or hostile environments for particular species and breeds. Furthermore, the livestock sector generates 37 per cent of anthropogenic methane, in addition to carbon dioxide (9 per cent) and nitrous oxide (65 per cent) (Steinfeld *et al.*, 2006). Given the great diversity between regions and species, the options for specific livestock production systems will need to be defined, and the trade-offs assessed. Tailored approaches are needed to avoid simplistic solutions to diverse and complex livelihood systems, so that they can meet the demand for livestock products in an environmentally sound and economically sustainable way.

53. How can middle and small-scale animal production be made suitable for developing countries in terms of environmental impact, economic return and human food supply and what should be the key government policies to ensure that a balance between the two is implemented?
54. What are the priority efficiency targets for livestock production systems (e.g. the appropriate mix of activities in different systems, the optimal numbers and types of animals) that would enable these systems to meet the demand for livestock products in an environmentally sound, economically sustainable and socially responsible way?
55. What are the effective and efficient policies and other interventions to reduce the demand for animal products in societies with high consumption levels and how will they affect global trade in livestock products and the competitiveness of smallholder livestock production systems in poor countries?
56. In addition to livestock production, how can inland and coastal fish farming contribute to a more sustainable mode of animal protein production in developing countries?
57. What are the best means to encourage the economic growth of regional livestock markets, while limiting the effects of global climate change, and what can industrialized countries do to improve the carbon footprint of its livestock sector?
58. What are the environmental impacts of different kinds of livestock-rearing and aquaculture systems?

Section 3: Agricultural development

Social capital, gender and extension

Social capital describes the importance of social relationships in cultural and economic life and includes such concepts as the trust and solidarity that exists between people who work in groups and networks, and the use of reciprocity and exchange to

build relationships in order to achieve collective and mutually beneficial outcomes. Norms of behaviour, coupled with sanctions, help to shape the behaviour of individuals, thereby encouraging collective action and cooperation for the common good. Social capital is thus seen as an important pre-requisite to the adoption of sustainable behaviours and technologies over large areas, as well as a precondition for the sustainable management of certain resources and technologies. Farmer participation in technology development and participatory extension approaches have emerged as a response to such new thinking and farmer involvement enables novel technologies and practices to be learned directly and then adapted to particular agroecological, social and economic circumstances (Godfray *et al.*, 2010). Farmer participatory research, on-farm testing and farmer selection of plant materials will need increasingly to be embedded in research, extension and development institutions. Agricultural advisory and extension services are a vital element in the whole research for development process and a range of market and non-market entities and agents provide critical services in support of improving farmers' and other rural people's welfare (World Bank, 2007; Anderson, 2008).

Changing agricultural research and development from current biases towards male farmers to gender-equitable is not merely an issue of political correctness or ideology; it is a matter of development effectiveness that can benefit all of society. Creating a gender-equitable agricultural research and development system is a transformative intervention, leading to opportunities, commodities, relationships and services that ultimately change the way people do things. By understanding both the constraints and opportunities for women in agriculture, it will be possible to develop new ways to address their needs and enhance their contributions in order to improve agricultural productivity, food security and poverty reduction (Meinzen-Dick *et al.*, 2010). What will also be required will be new metrics of social change and institutional learning.

59. As agriculture is highly knowledge intensive and institutionally determined, what is the effectiveness of different novel extension strategies and how best can they be set up to facilitate institutional change and technical innovation with the aim of ensuring that the widest number of farmers are reached and engaged?
60. How much can agricultural education, extension, farmer mobilization and empowerment be achieved by the new opportunities afforded by mobile phone and web-based technologies?
61. Which models and mechanisms for private sector funding or co-financing of extension advisory systems have most successfully reached farmers otherwise excluded from public sector extension services?
62. What are the most effective approaches for retaining women in research and extension systems and ensuring that they are fully involved in the design of research and extension systems to meet both gender-specific and wider needs?
63. What are the best social learning and multi-stakeholder models (e.g. farmers field schools) to bring together farmers, researchers, advisors, commercial enterprises, policy makers and other key actors to develop better technologies and institutions, for a more equitable, sustainable and innovative agriculture?

Development and livelihoods

Securing livelihoods, in particular rural livelihoods, rather than raising income, is an organizing principle for much development assistance, with a major focus on livelihoods diversification as a means of lifting people out of poverty (Ellis, 2000; InterAcademy Council, 2004; Barrett and Swallow, 2006) and on the role of agricultural intensification, farm and off-farm income, and agricultural inputs. De-agrarianization, especially in the BRIC countries (Brazil, Russia, India, China), but also in sub-Saharan Africa, is a noted phenomenon (Bryceson, 2002). Increasing food insecurity has also been related to the declining investments in agriculture worldwide, and has prompted renewed interest in agriculture, evidenced by the recent launch of a Global Agriculture and Food Security Program by the World Bank and other donors in April 2010, and calls for a 'new green revolution' to drive development in Africa (e.g. UNCTAD, 2010).

The impacts of environmental change and climate change are critical to how agriculture, poverty, development and livelihoods are understood and to what extent interventions can be effective. There has been a strong focus on the food security implications of climate change, including a new initiative within the Consultative Group on International Agricultural Research (CGIAR) (see www.ccafs.cgiar.org/). The emphasis on ecosystem services is reflected in several key reports by the World Resources Institute and FAO, both of which promote Payments for

Ecosystem Services as a potential means of lifting poor rural households out of poverty (FAO, 2007; World Resources Institute, 2008). But for each of these technical and market-based interventions, a set of critical questions remain about their impacts on inequality, environment and longer term resilience of households, communities and livelihoods.

64. What is the impact of agricultural subsidies in Organisation for Economic Co-operation and Development countries on the welfare of farmers in developing countries?
65. What systematic approaches can be used to identify and adapt technical options for increasing land and water productivity of rainfed crop and livestock systems so that they contribute to poverty reduction in different agroecological and socioeconomic situations?
66. What are the society-wide trade-offs among efficiency, social equity and environmental outcomes for agricultural development in societies with large rural and smallholder populations?
67. What are the best options to improve the sustainable intensification of agriculture?
68. How can the transition from today's smallholder-based agriculture to sustainable agricultural intensification occur in ways that maintain livelihoods for smallholder farmers?
69. What are the long-term impacts of international donors and aid enterprises on target beneficiaries in terms of food security, environmental sustainability, local economies and social inclusion?
70. How can interdisciplinary frameworks integrating scientific innovation and multi-stakeholder perspectives be designed and effectively applied to farming systems within developing countries?
71. Under what environmental and institutional conditions will increasing agrobiodiversity at farm and landscape scales result in increased livelihood opportunities and income?
72. Who will be farming in 2050, and what will be their land relationships (farm ownership, rental or management)?

Governance, economic investment, power and policy making

Promoting agriculture for development presents a serious challenge of managing multiple agendas and collective interests of formal and informal institutions (the state, the private sector and civil society), and their inter relationships, their obligations, processes, mechanisms and differences. It is precisely at this interface that governance, economic investment, power and policy making converge and play their respective critical roles.

On governance, it is important to establish safeguards against risks and assurances for the wellbeing and social and economic benefits to smallholders, where the state has an important role in influencing technology and policy options. Thus external aid and delivery models, and the state's policy guidelines, are important issues (World Bank, 2007; Royal Society, 2009). To achieve rapid agricultural and rural growth requires a range of complementary investments across the broad spectrum of agricultural production systems, from the large mechanized more intensive systems to smallholder units. Thus questions as to the best mix of public and private sector investments in irrigation and water management, rural roads, agricultural finance and extension services, among others, for the more intensive systems assume great importance (Lele *et al.*, 2010). Given the severe adverse effects of climate change on agricultural productivity in various agroecosystems, it is imperative that in addition to infrastructure investments, serious consideration be given to questions of adaptation through resilience of crops and cropping systems (Pretty, 2003).

73. What will be the consequences to low-income countries of the increased political roles of countries with growing economic and purchasing power (e.g. Brazil, China, India, Indonesia) in global food systems?
74. What is the effectiveness of various aid delivery models for multi- and bilateral donors for increasing the well-being and productivity of smallholder farmers in poorer developing countries?
75. Under what circumstances do investments in smallholder agriculture compared with larger and more mechanized farms achieve the greatest societal and environmental good?
76. What are the consequences of different mixes of public to private investment in irrigation infrastructure?
77. What are the consequences of different choices of investments in the resilience of agricultural systems to address the multifaceted adverse effects of climate change?
78. What steps need to be taken to encourage young people to study agricultural science?

Section 4: Markets and consumption

Food supply chains

The food supply chain (FSC) encompasses all those activities that lie between on-farm production and the point of consumption. FSCs have experienced fundamental change since 1950, becoming increasingly global in extent and marked by upward trends in scale of production, number of lines of manufactured products and levels of economic concentration by sector. The governance of FSCs has consequently become more complex and multi-scalar, involving many public, private and civil society actors (Lang *et al.*, 2009).

During the last two decades, it has become increasingly apparent that the primary locus of power within the FSC has moved steadily downstream towards the buying desks of the major corporate food retailers (UK Food Group, 2003). Three-quarters of food sales in most industrialized countries now pass through supermarket checkouts. This has drawn critics to highlight the environmental implications of extended supply chains designed to achieve year-round provision at the lowest cost. Yet, this retail format is becoming increasingly prevalent worldwide with rapid growth rates in many developing countries (Reardon and Gulati, 2008), and concerns raised about the dietary implications (Hawkes, 2008).

Vital work needs to be done to establish more precisely what 'sustainable food' represents, and to identify best practice standards across a wide range of activities throughout the FSC. While life cycle assessment and other technical measures will be needed to evaluate energy, carbon and water footprints and other environmental impacts, social, economic and ethical criteria will also be required in calculating appropriate trade-offs (van Hauwermeiren *et al.*, 2007; Edwards-Jones *et al.*, 2008). Ultimately, the purpose is to better demonstrate the link between diet and environmental impact (Frey and Barrett, 2007) and social impact, thereby encouraging greater personal responsibility and behavioural change (Jackson *et al.*, 2008) in the development of more sustainable FSCs.

79. How might a unified sustainable food standard be developed and implemented across trading blocs, such as European Union or North American Free Trade Agreement, to serve environmental, health (nutrition), food quality and social values, and how could this be effectively communicated to shape food purchasing behaviour?
80. Where is food waste greatest in food chains in industrialized and developing countries and what measures can be taken significantly to reduce these levels of food waste?
81. What is the best way to make food chains more resilient to exogenous trends (e.g. the upward price of hydrocarbons) and shocks (e.g. disruption to air freight)?
82. What is the potential contribution of localized food production to the overall sustainability of food systems?
83. How might appropriate limits be established on national per capita levels of meat consumption, while recognizing projected demographic and economic growth, given the aggregate impact of global livestock numbers particularly in relation to feed requirements and waste streams?
84. What are the best indicators that could be used to define agricultural sustainability thresholds (e.g. soil condition, biodiversity, nutrient cycling, energy use, key biological processes such as pollination) and how might these be communicated through the food chain?
85. What are the best institutional mechanisms to manage food stocks, storage, distribution and entitlement systems to ensure continued and sustainable supplies of food?
86. How can we expand the range and commercial development of food plants (given calorie dependence on the seven key crops of wheat, rice, maize, potatoes, soya, sugar cane and sugar beet) in order to enhance resilience in food chains while retaining genetic diversity in crops and their wild relatives?
87. How much land in agricultural regions should be left as natural habitats to provide ecosystem services and mitigate climate change threats?

Prices, markets and trade

In recent decades, domestic patterns of food production and consumption have become interconnected by global markets, and today we rely on both international and national markets to allocate food to consumers and distribute inputs used in food production. In 2008, the cost of global food imports exceeded one trillion US dollars, having grown substantially in the two preceding years (Popp, 2009). The new economics of food mean that small changes in production can lead to large fluctuations in price. Most countries now rely on buying their

food on open global food markets; however, when national governments seek to protect their own supplies, market chains can break down (Royal Society, 2009).

In 2007/2008, the world food markets witnessed extreme food price spikes in a number of key agricultural commodities, including wheat, maize and rice. Causal factors are now understood to include regional declines in agricultural productivity, falling global stocks in grains, speculative trading and erection of trade barriers (Defra, 2008, 2009; Wiggins, 2008). The price spikes led to riots in Morocco, Mexico, Indonesia and elsewhere. This political instability was a result of a number of short-term pressures, but it highlighted a long-term problem of food security and its impact on human well-being (Royal Society, 2009), particularly for low-income households that spend anything up to 75 per cent of their income on food (Naylor *et al.*, 2007). Policy research over the coming years will therefore have a key role to play in the design of mechanisms and instruments that minimize or alleviate the effects of such market failures.

88. What priority investments are needed to develop effective input and output markets in the poorest developing countries (especially sub-Saharan Africa)?
89. As energy prices rise, how can agriculture increase its efficiency and use fewer inputs and fertilizers to become economically sustainable and environmentally sensitive, yet still feed a growing population?
90. What mechanisms can be devised to buffer against growing market volatility and subsequent risk for farmers and under which conditions do different mechanisms work best?
91. How can market-based food supply systems be developed that offer economically sustainable levels of financial reward to all participants in the food chain (i.e. farmers, processors and retailers) while simultaneously providing safe, nutritious, natural resource-stewarding and affordable food to consumers?
92. What mechanisms will provide incentives for further investment in sustainable, high-yielding agriculture that also maintains ecosystem services?
93. What mechanisms for institutional capacity can be used to create an efficient and equitable global marketing system so that food is produced in an economic and ecologically efficient manner and traded appropriately to achieve food security?
94. How can national food security policies be designed to be more compatible with worldwide open market food policies while securing the interests of local farmers and equitable access to food?

Consumption patterns and health

Increased purchasing power, shifting food preferences, access to global markets and growing populations have led to significant shifts in consumption patterns in recent years that are anticipated to continue into forthcoming decades. Daily per capita calorie consumption has increased from 2280kcal in the 1960s to 2800kcal shortly after the turn of the century. Furthermore, annual per capita meat consumption has increased from 11kg in 1967 to 24kg three decades later (Lobley and Winter, 2010). As income levels rise in developing countries, so it is expected that demand for meat will tend towards the per capita consumption rates of 115kg per year in the USA and 80kg per year in the UK (Royal Society, 2009). In China alone, meat consumption has more than doubled in the past 20 years, and is projected to double again by 2030 (Scherr and Sthapit, 2009). As a consequence of increasing demand, meat production is expected to grow from 229m tonnes in 1990 to 465m tonnes by 2050, and milk is expected to grow from 580 to 1043m tonnes (Steinfeld *et al.*, 2006). Shifting consumption patterns combined with population growth have led to estimates that food production will be required to dramatically increase to meet growing consumption needs in the future (Lobley and Winter, 2010).

The emergent pattern of dietary shifts is unlikely to provide the same health benefits as well-balanced diets rich in grains and other vegetable products. Increased meat and dairy consumption (particularly red meat), combined with increased intake of high sugar and high fat foods characteristic of modern, highly processed food products, are likely to lead to nutritional deficiencies as well as a growing number of cases of obesity and its associated illnesses, such as Type II diabetes and chronic heart conditions. This will increase the demand for healthcare and lead to increased spending in this sector (Royal Society, 2009).

95. How will predicted changes in meat consumption across different countries affect demand for the range of agricultural produce?

96. What information is most useful to consumers wishing to make informed decisions about the environmental and social impacts of their food choices and can intervention methods be developed that encourage and provide incentives to all consumers to eat healthy diets?
97. Under which conditions can governmental health policy successfully affect consumers' diets by promoting good food as preventative medicine?
98. What programmes (or combinations) are most effective in promoting broad-based access to healthy food across different socioeconomic groups?
99. How effective are experiential learning programmes (e.g. garden-based learning, wilderness therapy, forest schools, outdoor learning) in promoting child nutrition, healthy child development, and prevention of obesity and diabetes?
100. What is the effectiveness of different systems aimed at enabling informed consumer choice to directly reward farmers and thereby encouraging the spread of positive environmental attributes in food production (e.g. direct distribution networks organized by farmers, labelling schemes on food, information on farm websites)?

Discussion

The horizon-scanning approach described here has generated 100 questions considered to be of primary importance to global agriculture and food security. If answered, it is anticipated that these questions will have a significant impact on global agricultural practices worldwide, while improving the synergy between agricultural policy, practice and research. The questions are wide-ranging, are designed to be answerable and capable of realistic research design, and cover 14 themes identified as priority to global agriculture. Compiled through consultation with senior representatives and experts from the world's major agricultural organizations, professional scientific societies and academic institutions, we hope the questions will guide policy makers involved in directing future agricultural policy and research, and researchers looking to direct and prioritize their own efforts and programmes of work, in addition to building a structured dialogue between these groups. There are, however, limitations to this approach. Firstly, the final list of questions was inevitably a product of the initial 618 questions submitted, the Core Group members and the processes of sorting, rewording and voting that followed. By consultation with a large group of experts from a wide range of organizations with diverse expertise, we hope to have minimized the effect of individual preferences and directed choices.

One of the biggest challenges of this process was to formulate questions that are answerable through research design, and yet suitably generic to encompass the broad issues that relate to global agricultural systems at a variety of scales (Sutherland *et al.*, 2006, 2009). In rewording the questions to ensure brevity and clarity, the final list of questions undoubtedly masks the complexity of some of the issues involved. We believe, however, that in developing a research strategy to address the questions, or elements of them, most of the questions can be broken down into component parts, or projects, that can be tailored to specific social, ecological and economic settings. What is now needed are processes to prioritize these actions in different regions of the world and effective mechanisms and metrics to assess their impact.

In generating this list of questions, we hope to contribute to the many dialogues between scientists, practitioners and policy makers driving agricultural research and discourse in future years. As well as guiding (teams of) researchers looking to prioritize their own research efforts and draw up directed programmes of research, we hope that the questions will guide policy makers looking to support and direct the agricultural research needs of coming years, and funding bodies and organizations looking to target their investment and support of agricultural science. Improved dialogue and information flow between policy makers and scientists is vital if agriculture is to overcome the challenge of dealing with multiple drivers of population growth, dietary shifts, energy insecurity and climate change. The agricultural sector is now at the heart of this unprecedented combination of drivers, and evidence-based policy will be essential to overcoming the lack of understanding between agricultural research and policy direction and improving collaboration in the sector as a whole.

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