



Introduction

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Achieving food and environmental security: new approaches to close the gap

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1. Introduction

Achieving food security in a 'perfect storm' scenario is a grand challenge for society. Unless 50% more food, 50% more energy and 30% more freshwater are available by 2030, a 'perfect storm' is envisaged where there would be simultaneous shortages of all of these on a global scale [1]. This becomes an even more 'wicked problem' when climate change and an expanding global population act in concert, making the challenge of achieving global food security even more complex and demanding.

Food security 'exists when all people, at all times, have physical and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life' [2, Plan of Action no. 1]. It is determined by four factors: (i) availability (from agricultural production and land-use or exchange); (ii) stability of supplies (e.g. seasonally and from year to year); (iii) access (dependent on financial means but also physical access and social factors); and (iv) biological utilization of food (e.g. nutritional diversity and food safety issues) [3]. It is estimated that almost one billion people face hunger through lack of macronutrients [4], and a further one billion lack sufficient micronutrients, leading to both negative health and development outcomes [5].

Millennium development goal (MDG) number 1 (eradicate hunger and poverty) is effectively coupled to many of the other MDGs; it is imperative that we develop mechanisms to meet MDG 1 and other goals that are complementary and which do not oppose one another. For example, sustainable intensification (SI) of agriculture has been proposed as a way to address hunger while also minimizing further environmental impact. However, the desire to raise productivity and yields has led historically to environmental degradation, reduced biodiversity and limitations to ecosystem services, with the greatest impacts falling upon the poor. Addressing MDGs in isolation can, therefore, be at the expense of others, and improved integration of actions is required. We must increase food security sustainably and in a climate change-resilient manner, while also reducing greenhouse gas emissions, alleviating poverty and conserving biodiversity [4–7]: perhaps the greatest challenge that we have ever faced.

The relationship between food security outcomes and the environment is complex and multidimensional [8]. Food security is dependent not only on (non-provisioning) ecosystem services, but it is also one of the greatest drivers of the loss of ecosystem services. The pursuit of food security through increased agricultural production may include changes in land use, land cover, management practices and agricultural inputs, and it a key driver of landscape change [9].

The concepts of planetary boundaries and 'safe operating space' have already had a significant influence on the international discourse about global sustainability [10]. Nine interlinked ecological boundaries have been defined at the planetary scale, and it is argued that society should remain within these if it is to avoid 'disastrous consequences for humanity'. Three of these (biodiversity loss, climate change and nitrogen cycling) have all been exceeded, and all are linked to agricultural intensification. A recent and novel framework for considering this concept has been proposed by economists from Oxfam [11]. The 'safe and just operating spaces' (doughnut) idea argues

for the need to live within the 'space' that lies beneath the planetary boundary, yet above the social floor of basic and just needs for food, energy and water security, and social goods such as education and healthcare.

How do we deliver food security for all, without further exceeding planetary boundaries that have already been breached? Many of these social and just boundaries are linked to the MDGs and will undoubtedly be within the emerging sustainable development goals planned for post-2015. Science must play a central role in providing innovative solutions to these challenges, and this special issue of the *Philosophical Transactions of the Royal Society B* captures a Discussion Meeting ('Achieving food and environmental security: new approaches to close the gap') that took place at the Royal Society, in London between 3 and 4 December 2012, to explore some of avenues that science is currently pursuing. It invited prominent speakers to report on (i) the challenges that we face in achieving food and environmental security, (ii) research and extension in pursuit of sustainable production intensification, (iii) innovation for sustainable agriculture and (iv) using the ecosystem services framework for managing agricultural ecosystems.

Following the London meeting, a workshop was held at the Kavli International Centre between 5 and 6 December 2012. Discussions at this meeting focused on reviewing the key issues, barriers and opportunities for science to contribute towards the new global agricultural systems that are needed to deliver food security. From this workshop, a statement 'The Kavli Declaration: a vision for agriculture in 2050' was developed. All of the attendees at the Kavli workshop have signed the declaration, which is presented in box 1.

2. The challenge we face

There have been many recent reports outlining the challenge we face [5,6,9], and a widely debated contribution to a solution relates to the idea of SI of agriculture, which was previously highlighted in a Royal Society report led by Sir David Baulcombe [12]. One of the main proponents of this concept is Charles Godfray, who chaired the UK Foresight report in 2011. Godfray explores the global food system, which is important as it places the role of agricultural production in context and addresses all the pillars of food security rather than an overemphasis on the availability (production) pillar [13]. The significance of SI to this broader picture is described and how it needs to fit into policies that encompass the food system. There is still much to unravel in terms of the impact that SI can have on global food security, but, importantly, this paper creates a framework from which to advance.

After a period of decline, agricultural research is now receiving more funds and has climbed up the priority list of governments and funding agencies. Beachy's [14] paper provides convincing evidence of the tremendous return on investment from agricultural research and development. Focusing on the USA as a model system, he estimates that there is an up to 40-fold return on such investment. This should bring confidence to funders, taxpayers and industry, all of which need to respond to the global need for increased investment in agricultural research. His call to arms challenges governments to increase expenditure, compared especially with energy, health and information technology. He also outlines ways in which research structures and mechanisms

for allowing transfer of technologies will need reconfiguring to allow research to respond to the global food security challenge and deliver successful solutions.

Sub-Saharan Africa raises the greatest challenge for addressing food security. Rapid demographic change, coupled with climate change and extreme weather events, has resulted in high levels of poverty and hunger. While hunger levels have been reduced in Africa since the 1990s, one in three of the population is undernourished despite the agricultural potential of the African continent [15]. Chiota and co-workers [16] use lessons from Lake Chilwa in Malawi to illustrate ecosystem and livelihood resilience for the 1.5 million people directly reliant on services from the Lake Chilwa basin. The shallow lake is very susceptible to erratic rainfall and high evaporation rates, threatening a drought in the very near future. The Lake Chilwa example is relevant to many other lake systems in Africa and is an example of the importance of using an ecosystem services framework to manage for food and environmental security.

3. Sustainable production intensification: research and extension

The concept of SI [17] embraces many of the themes of this special issue in a general sense, but consensus is yet to emerge concerning its operationalization. Given the need expressed by many papers within this issue, to embrace priorities for crop production while protecting human health and the environment, there was a consensus that a concept such as SI could facilitate effective policy and practice during the transformation of agricultural systems that meeting participants identified as a global priority (see Kavli Declaration at the end of this article). To be effective, this concept must be broad enough to encompass both intensive agricultural systems in the developed world and smallholder agriculture internationally, but particularly in less developed countries. Although SI has been identified by the UN Food and Agriculture Organization as an appropriate pathway for smallholder agriculture to pursue [18], the practices outlined in 'save and grow' give very limited recognition to the opportunities provided by the plant sciences, and they do not address either the scale or complexity of the challenges to production that we face. The four papers in this part of the meeting all represented large-scale, current programmes that are actively engaged in research, education and analysis of agricultural systems in developing countries. Three of the papers include both US and African authors, and all of them provide evidence of the functional international cooperation that is critical for effective progress.

Bill Settle and co-workers review the strengths and weaknesses of participatory approaches to agricultural extension, particularly farmer field schools [19]. Farmer field school methodologies enable more adaptive crop management by farmers, based upon experiment and observation, and they promote farmer participatory research, both of which may provide for a higher likelihood of successful implementation of new technologies. Although technology adoption may become an important theme for the future, and the vehicle through which much of the new science reported in the journal issue could be adopted, the emphasis of farmer field schools to date has by necessity been reduction or modification of practices that have an adverse effect on

environment, health and production. Settle and co-workers report a new analysis of data from Malian cotton production regions that illustrates the impacts of farmer field school education over an 8 year period, and the progressive reduction in pesticide purchasing in areas receiving this education, with no apparent reduction in yield [20]. The evidence for progressive adoption of reduced-pesticide cotton management indicates that diffusion of this approach may be occurring between farm households. The possible reasons for this diffusion include the access by farmers to effective education, combined with efficacious, less hazardous and economic alternatives to broad-spectrum pesticides.

Bill Settle and co-workers argue that more quantitative and scientifically based impact assessments are needed for large-scale education interventions, and the paper by Anderson *et al.* with US and West African authors [21] reports a capacity-building programme for pesticide residue monitoring and analysis in West African surface waters that addresses this need. Passive sampling devices offer many practical and methodological benefits for the analysis of water-borne contaminants, and effective deployment in Africa would open up possibilities for water quality management, and the protection of fisheries, aquatic biodiversity and drinking water that currently do not exist. Anderson and co-workers summarize a multi-year capacity-building programme that is partnering US and West African laboratories and engaging in the joint analysis of environmental samples through a process that integrates research, and technical and professional development for both laboratories. Unusually for papers on capacity building, they chart both their successes and failures, and illustrate that effective partnerships must be long-term and tackle infrastructure and support for West African laboratories as well as training of personnel. In one of the first detailed analyses of contaminant burdens in irrigated West African agricultural systems, they detected legacy and current-use pesticides, and a number of other anthropogenic pollutants of concern.

Also working in the Niger and Senegal River basins, Jepson [22], with US and West African co-authors, outline new analytical methods for human health and environmental risk assessment for pesticides, and then use these, for the first time, to analyse pesticide use data from five West African countries. Based upon detailed surveys from villages across these large river systems, they report high levels of use of broad-spectrum pesticides in locations where literacy and pesticide safety education are limited or non-existent, and where child exposure at hazardous levels is certain to occur. Jepson and co-authors developed a novel multi-scale framework for reporting pesticide risks that they analysed at the regional, national and local, village scales to inform policy development, regulation and local risk management, respectively. Their analysis reveals high levels of risk to terrestrial and aquatic wildlife and to villagers throughout West Africa, with a high proportion of the total irrigated production area in this region subject to the impairments to health and ecological integrity that result from exposure to broad-spectrum pesticides. This analysis portrays West African agricultural systems as they currently exist, and Jepson and co-workers argue that this system will continue to provide a weak platform for the adoption of new agricultural technologies until both regulatory and educational systems can respond effectively to health, environmental and production risks.

Given the many choices and opportunities that farmers will face, and their inherent aversion to risks, Antle and co-workers

[23] provide an analytical simulation modelling framework that explores trade-offs between production, economics and environmental protection under systems that represent realistic alternatives for adoption. Their methodology represents an advance over current modelling regimes by incorporating behaviour, including self-selection in adaptive responses by farmers to both technological and environmental change. In a case study, Antle and co-authors analyse options for nutrient management by Kenyan maize farmers, and they explore how poverty levels in the farming population as a whole are affected by the adoption rate for a new nutrient management regime. As adoption rates increase, expected returns among adopters decline and those among non-adopters increase, but at the predicted adoption rate, a higher proportion of the adopters are above the poverty line. Antle and co-authors outline new techniques that make maximal use of locally available data, and they address critical aspects of the granularity of agricultural systems that are important drivers of technology adoption.

A theme for all four papers in this segment of the special issue is that for SI to become operationalized, locally derived data are required, in combination with effective and state-of-the-science analytical tools. The tools and approaches reported in this section may be used for analysis of the learning associated with agricultural extension, for monitoring and analysis of environmental chemicals, for risk assessments that encompass pesticides and other technologies and practices, and for trade-off analysis for farmers, and they constitute part of the sophisticated toolbox that will be needed if SI is to succeed.

4. Innovation for sustainable agriculture

Following on from the Royal Society policy statement and reports on the SI of agriculture [12], papers in this section were concerned with the development of innovative approaches to agricultural sustainability, by protecting crops from biotic losses while at the same time minimizing seasonal inputs. Increased protection is essential, so that the investment of land preparation, seed, water and the provision of nutrients are not wasted. The ultimate objective is to deliver increased protection and reduced carbon footprint via the seed, while at the same time enhancing improvement of plant performance, molecular breeding, exploiting species diversity by use of companion plants and genetic modification (GM). The overriding objective for this section was to highlight new science in this area that will underpin new global agricultural systems.

Turlings and co-workers [24] explain the potential for improving plant performance by means of plant strengtheners or elicitors as agents that, when applied to crop plants, would boost their vigour, resilience and performance. Evidence from currently available compounds, such as the commercial compound acibenzolar-5-methyl and the natural product laminarin in increasing release of attractants for improved conservation biological control of herbivorous pests by parasitoids (i.e. parasites that kill their host) is given. This is followed by describing how the new ideal elicitors would be identified using a genetic screening approach.

The delivery of repellents against herbivorous pests (push) coupled with parasitoid attractants and herbivore attracting trap crop (pull) via companion plants is described in a push-pull system for small holder sub-Saharan African cereal farmers by Khan and co-workers [25]. The companion plants were identified by surveying species diversity in the region, and the

programme underpinned by scientific evidence showing the nature of the push and pull chemistry. The former involved isoprenoid oxidation products that both repelled pests and recruited foraging parasitoids. Weed control, particularly of the African witchweed *Striga hermonthica*, was provided by another set of chemicals, C-glycosylflavonoids, released into the rhizosphere by intercrop companion plants, *Desmodium* species, a valuable cattle forage legume also providing a source of fixed nitrogen. The sustainability of this system in dramatically raising small holder farmer yields suggested this system for dissemination in the immediate future to one million in the region and moving to companion plant species with drought tolerance.

Jones and co-workers [26] describe the latest in understanding host/pathogen coevolution, which is now showing new ways to breed and develop GM approaches to manage pathogens via the seed. To succeed, pathogens must suppress host defence mechanisms using molecules known as effectors that are usually delivered into host cells. However, plant resistance genes confer activation of defence upon recognition of effectors. This understanding provides new opportunities to deploy resistance genes in a way that could enable durable disease control. Evidence for the value of this type of approach was provided by a GM blight-resistance field trial using the Rpi-vnt1.1 gene isolated from a wild relative of potato, *Solanum venturii*, and introduced, by GM methods, into the potato variety Desiree.

Similarities between the highly effective currently registered pesticides and plant defence chemistry based on secondary plant metabolites are raised by John Pickett as a reason to consider exploiting such metabolites in new GM strategies and because genes for natural product biosynthesis are now available [27]. Although more complicated pathways are involved compared with more current pest resistance traits developed by breeding or GM, routes to secondary metabolites can now be seen as promising targets, and some were offered with evidence of laboratory success to date, for example, the aphid alarm pheromone and the isoprenoid oxidation products relating to plant stress discussed in previous papers, particularly the push–pull system. Taking the delivery of sustainable pest management via the seed to a stage further towards perennial arable crops would require new pest management tools, and sentinel plants that respond more sensitively to the pest, disease or weed development could provide early warning of attack and then release stress-related elicitors to switch on defence in neighbouring intact crop plants, thereby obviating external delivery and promoting non-constitutive defence embedded in the planting material.

5. Using the ecosystem services framework for managing agricultural ecosystems

The Millennium Ecosystem Services report was a seminal publication, which has had major impact both scientifically and politically [28]. A series of national assessments have used the approach [29,30], and the framework is becoming widely adopted/considered for future land-use management decision-making. While there has been debate about how best to account for the ‘value’ of services [31,32], the ecosystem services concept is gaining significant political ground and is even helping shape ideas relating to biodiversity offsets (Valuing Nature UK) and payments for ecosystem services other than carbon trading through Reducing Emissions from Deforestation and Forest Degradation (REDD)

and REDD+ [33,34]. It certainly provides a useful framework for developing concepts such as SI of agriculture and how to achieve food security alongside environmental stability and it is pertinent to several MDGs.

Delivering food security requires four pillars to be addressed simultaneously, and the sustainable/resilience pillar is often neglected in the rush for short-term solutions, which can lead to a ‘tragedy of the commons’, in which key services may be lost [35]. In this final series of papers, environmental stability is addressed in a food system context, hopefully managing to ‘close the gap’—a central aim of the discussion meeting.

Phalan and co-workers [36] paper addresses the issue of land sharing versus land sparing. The debate about whether to extensify or intensify agriculture raises many issues and often draws few conclusions. Phalan’s work focuses on biodiversity, using birds as a case study, and explores whether sparing land for nature through intensification is better than the sharing land with nature that would result from extensification practices. This analysis concludes that in most situations, bird biodiversity is best delivered through sparing land, and thus intensifying agriculture, in order to spare land. This is the preferred solution in terms of sustaining bird biodiversity and in food provisioning. Importantly, the land that must be spared to allow biodiversity to thrive could also be managed to deliver a range of ecosystem services that are not well delivered through agriculture. During the Kavli Meeting, it was highlighted that spared land must also be maintained as well as managed and should not simply represent a temporary sparing, only to be farmed shortly after in the quest for more food.

While the concept of ecosystem services provides powerful and important ways of visualizing and valuing what we derive from ecosystems, our ability to measure and model them must advance. Several large consortia have developed modelling approaches, including InVEST and ARIES. Ferdinando Villa, who has led the development of ARIES (Artificial Intelligence for Ecosystem Services), outlines how this modelling framework can allow multiple services, serving many beneficiaries to be modelled [37]. Importantly, the flow of these services is encompassed within Bayesian methods to accommodate the uncertainties that are encountered in the data-scarce situations common to ecosystem services research. Food provisioning is an important ecosystem service which relies upon, and also affects, other ecosystem services [9]. The use of a model such as ARIES allows scientists to quantify these services, their interactions and flows and determine the trade-offs among differing beneficiaries that will be required to deliver food security.

Across the tropics, smallholder farmers face numerous risks to agricultural production from a complex range of biotic and abiotic stressors. For poor farmers, such losses to production can significantly affect their livelihoods and well-being, as well as their food security. Working in Madagascan communities, Harvey and co-workers [38] explore the extreme vulnerability of smallholder farmers to agricultural risks and climate change. Using participatory approaches, they surveyed 600 households in three regions of Madagascar in order to identify coping strategies to a range of challenges which result in more than 70% of farmers producing insufficient food for their families and a hunger season of over three months per year. In spite of over 90% of farmers perceiving changes in climatic conditions, only a few have developed adaptation and management strategies to reduce the risks. It is clear that there needs to be changes in agricultural policies to address the risks associated with climate change, as

experienced in much of sub-Saharan Africa. Risk management is needed to improve food security and resilience to climate change, and using ecosystem services as a framework could enable more effective progress to be made.

Because the MDG associated with hunger and poverty interacts with MDGs associated with environment, health and well-being, it is essential that we look for approaches that can deliver multiple goals. In the last talk of the discussion meeting, Poppy and co-workers [39] outlined the use of an ecosystem services framework in order to deliver both food security and environmental stability. More than 550 million people live at the agricultural–forest interface, and many of these people are poor and food insecure, especially when deforestation has been rapid and/or extensive. Using a case study from the Zomba region of southern Malawi, a research programme is described that allows eco-

system services to be quantified, and the links to food and nutritional security to be described along negative feedbacks to services. An interdisciplinary approach of combining participatory methods, models and policy/governance frameworks is presented within the drivers–pressures–states–impacts–responses (DPSIR) framework, and illustrates the need to work at the right scale, something often neglected in national UN FAO statistics. The ecosystem services framework allows key issues in food security/environmental stability to be addressed, including scale, the identity of beneficiaries, trade-offs and the winners and losers from management and mitigation strategies. The last component represents a unique feature of the ecosystem services approach compared with conventional natural resource or ecosystem management approaches, yet it is crucial to delivering both food security and environmental stability.

The Kavli Declaration: A Vision for Agriculture in 2050

A two-day workshop was held on Dec 5–6th 2012 at the Kavli International Centre, Chichely Hall, Buckinghamshire, United Kingdom. During the last afternoon session, the participants sought to outline a vision for future agriculture, which we propose as the Kavli Declaration.

Participants at the meeting and whom have agreed the declaration are:

Professor Kim Anderson	Professor Jonathan Jones FRS
Professor John Antle	Professor Zeyaur Rahman Khan
Professor Andrew Balmford FRS	Dr Timothy Krupnik
Professor Roger Beachy	Dr Kelvin Peh
Dr John Bingham CBE FRS	Dr Ben Phalan
Dr Michael Birkett	Professor John Pickett CBE FRS
Professor Toby Bruce	Professor Guy Poppy
Professor Sosten Chiotha	Professor Alan Raybould
Ms Radhika Dave	Dr Mike Robson
Professor Keith Goulding	Dr William Settle
Professor Rhys Green	Professor Ted Turlings
Dr Celia Harvey	Mr Roberto Valdivia
Dr Andy Jarvis	Dr Ferdinando Villa
Professor Paul Jepson	Dr Simon Willcock

The Kavli Declaration:

By 2050, humanity will be unable to meet its needs for food through current agricultural practices. We must drastically transform the global agricultural system to deliver food security and net greenhouse gas absorption without losses of water availability and wild habitats. This can only be achieved by more resource-efficient agriculture. This will need to combine locally relevant crop and animal genetic improvement and resilient agronomic practices that harness local ecosystem services to minimize inputs and close nutrient loops while sequestering carbon. The success of these on-farm activities will depend on restoring degraded lands and safeguarding remaining natural habitats to ensure the continued provision of wider ecosystem services.

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