REVIEW OF BBSRC RESEARCH RELEVANT TO ENVIRONMENTAL CHANGE

A REPORT FOR BBSRC COUNCIL

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BIOTECHNOLOGY AND BIOLOGICAL SCIENCES RESEARCH COUNCIL

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REVIEW OF BBSRC RESEARCH RELEVANT TO ENVIRONMENTAL CHANGE

EXECUTIVE SUMMARY

Environmental change (including climate change) represents one of the greatest challenges facing humankind over the coming decades. Research will be essential to enable analysis and prediction of the changes and to allow the development of strategies for adaptation and mitigation of their impacts. Although only a small proportion of current BBSRC-funded research directly concerns environmental change, much research across the wide remit of BBSRC is also relevant, in providing underpinning knowledge of how biological systems function and respond to environmental factors.

Priorities for research

The panel assessed where future BBSRC-funded research can best contribute to addressing key problems in environmental change. While recognising that there are opportunities across much of BBSRC's broad remit, the panel concluded that research in relation to agriculture and food should take priority.

Recommendation 1: In relation to environmental change, BBSRC should adopt as the leading priorities research that will:

A. Predict the incidence of those pests and diseases of farm animals (including zoonoses) and crop plants that are likely to increase as a result of environmental change and develop measures to combat their spread and mitigate their impact

B. Develop new varieties of crops and livestock, and novel practices, systems and strategies to enhance the efficiency of agricultural production sustainably in response to environmental change

C. Explore new opportunities to mitigate environmental change through the emerging science of biogeochemical engineering

D. Improve the ability to predict and manage the effects of environmental change on soil systems, ecosystem function and services, and biodiversity conservation in agricultural and associated landscapes

Further details of these recommended priorities are included in the main body of the report. Among the priorities, we see **priority A** as the most urgent, and we advocate a new funding initiative that would build and integrate research capacity on crop and livestock diseases using systems-based approaches and mathematical modelling across a range of scales, and incorporating socio-economic aspects.

Coordination of research

Coordination of research and training across funders and stakeholders is essential in a field as broad as environmental change. We welcome the cross-funder Living with Environmental Change (LWEC) programme as a major new initiative to bring together funders and stakeholders and we endorse BBSRC's involvement in it. While we wait with interest to see how LWEC develops, there is a clear opportunity for BBSRC to capitalise on existing strengths and seize a leading role in research (within the Council's remit) on food, agriculture and the managed landscape, within LWEC and beyond. BBSRC must maintain investment both in the short and the longer term: environmental change research should be a major component of BBSRC's strategy in Spending Reviews for the foreseeable future.

Recommendation 2: BBSRC should develop a leading position with respect to food, agriculture and the managed landscape within the Living with Environmental Change

(LWEC) programme in view of its importance as a major cross-Council, and multi-stakeholder, programme. In the longer term, BBSRC should prioritise funds from the next spending review and beyond for sustained investment in research to manage the impacts of environmental change. This reflects the importance, magnitude and long-term nature of the challenges.

BBSRC institutes

BBSRC-sponsored institutes are among the UK's leading centres for research relevant to environmental change, particularly in the agricultural context. They are well placed to take a leading role and are already doing so, and this should be encouraged and facilitated by promoting collaborations across the institutes and more widely. Additional cross-institute programmes in relation to environmental change, for example in animal disease/ zoonoses/ food-borne pathogens, and in plant disease, could be valuable and Council should encourage the institutes to explore this. Furthermore, the institutes should form the basis of national facilities to enable wider use of their existing infrastructure and data sets, collections and other resources.

Recommendation 3: BBSRC should give every support to its institutes in engaging fully with research relevant to environmental change and especially addressing the priorities we have listed. Consideration should be given to further cross-institute programmes or other mechanisms that foster productive collaborations between institutes. BBSRC should ensure that there are no barriers that would prevent its institutes working together or in partnership with other research institutes, universities, industry or non-governmental organisations.

Recommendation 4: In taking the lead in agricultural and food research – for example under the LWEC programme – BBSRC should develop national facilities located at its institutes that can be accessed more widely by researchers working in the context of environmental change.

Innovation, translational research and partnership with industry

Combating the deleterious effects of environmental change and exploiting potential opportunities arising from changes in climate will require not only the development of novel techniques and approaches but also stimulation of translational research. There is a need for innovation across the spectrum of basic, strategic and applied research, coupled with the establishment of effective partnerships with industry and other end users.

Recommendation 5: To maximise economic and social impact BBSRC should increase the effectiveness of translation and exploitation of research relevant to environmental change through a number of mechanisms, in particular by:

- ensuring that the topic is highlighted as a priority throughout its various schemes to promote partnerships with industry
- working with the Technology Strategy Board and other funding partners to facilitate innovation and knowledge transfer
- exploiting the existing resource of its relevant institutes by ensuring adequate funding and appropriate career incentives / recognition for translational activities.

Facilities and collaboration

Progress in research on environmental change will require widespread access to and effective use of suitable facilities, including monitoring networks and associated data sets, both in the UK and internationally.

Recommendation 6: BBSRC should work with other funders in the UK and overseas to promote awareness of, availability of, and access to suitable research resources to address questions in environmental change. In particular, BBSRC should seek to be a partner in suitable international programmes sharing access to experimental sites, facilities and data. The Council should ensure that funding mechanisms are available to support UK researchers in international collaborations specifically in relation to environmental change.

Interdisciplinary approaches

The scale and complexity of some research questions in environmental change mean that interdisciplinary approaches are needed to integrate across disparate fields. Integration is needed in research across different scales of biological systems; to incorporate theoretical, mathematical and systems-based approaches; and to address economic and social aspects. The cross-funder Rural Economy and Land Use (RELU) programme was a useful model for the integration of socio-economic research with natural science, and should be considered as a way forward for work under the LWEC programme.

Recommendation 7: BBSRC should work with other funders to promote interdisciplinary research approaches to problems in environmental change, and in particular should build on the previous cross-Council programme Rural Economy and Land Use (RELU) in order to embed more thoroughly the consideration of social and economic aspects in biological and related research.

Training and skills

A continued supply of researchers with skills and expertise in relevant topics will be essential to allow future progress. Although not specific to environmental change research, skills shortages were identified in several disciplines (including some, such as plant breeding, that have been highlighted by previous reviews). BBSRC will need to contribute to efforts to address these needs, and especially skills in translational research that will be essential to maximise the uptake and application of the outputs of basic research.

Recommendation 8: Informed by this review and the forthcoming Skills Needs Review for the Environment Research Funders' Forum (ERFF), BBSRC should support and promote the provision of trained researchers in key topics within its remit that are needed to address questions relating to environmental change. Provision should include taught Masters courses, some of which could be developed in collaboration with BBSRC institutes and/or industrial partners.

Public and stakeholder engagement

There is a need for additional engagement with the public for research related to agriculture and environmental change, which is an area of increasing public interest. Funding initiatives developed under LWEC should include appropriate science-in-society activities.

Recommendation 9: BBSRC should engage wherever practicable with the public and other stakeholders on topics relating to environmental change. In particular, BBSRC should strongly encourage all holders of grants relevant to environmental change and BBSRC institutes carrying out research in this area to participate in public engagement activities. The lack of public acceptability of technologies such as genetic modification represents a barrier to addressing the challenges of environmental change and BBSRC must work with other stakeholders to promote effective dialogue.

FOREWORD

Origin of this review

1. This report is from a review panel established by BBSRC in 2007 under the chairmanship of Professor Alistair Hetherington (University of Bristol) to advise the Council on future directions for BBSRC research in topics relevant to environmental change, including (but not limited to) climate change.

2. The review is one in a series of BBSRC strategic reviews of scientific areas[1]. Such reviews have had significant impact on BBSRC strategy (setting scientific priorities and mechanisms for their implementation).

3. The review panel met four times between October 2007 and September 2008. The review process also included a consultation exercise, which elicited 49 responses; the review panel took these into account in formulating its recommendations.

Structure of the report

4. We begin by setting out in **Chapter 1** the background, including the broader context and the scientific scope to be addressed in the review (with reference to the roles, interests and activities of other relevant UK research funders). In **Chapter 2** we go on to set out recommended priorities for future BBSRC-funded research and in **Chapter 3** we propose mechanisms to promote their effective implementation. **Annexes** provide the terms of reference and membership of the review panel, further information on the consultation and a glossary of some technical terms used in the report.

Acknowledgements

5. The review panel would like to thank all those who contributed to this review, either by supplying information for the panel or by responding to the consultation. These contributions were invaluable in providing additional insight and informing the panel's discussions. The panel would also like to thank the review secretariat in BBSRC for their help and support throughout the review process and in producing this report.

[1] http://www.bbsrc.ac.uk/organisation/policies/reviews/scientific_areas

CHAPTER 1: BACKGROUND

6. We begin by setting out key aspects of the context for BBSRC research relating to environmental change. We go on to outline the scope of the review and provide background information on the roles, primary interests and scale of funding by the main relevant UK research funders.

Context

7. Environmental change driven by increasing human populations and economic development poses fundamental challenges for humankind. Climate change will be the most pressing of these over the coming decades. The weight of scientific evidence is that the earth's climate is already changing[2], and the unprecedented scale of the changes that are predicted will have impacts on many aspects of everyday life, and potentially all sectors of the economy[3]. Even temperature changes at the lower end of the range of predictions (e.g., increase of 2C by mid-21st century) would have significant impacts – including impacts on UK agriculture, with altered and more extreme weather patterns, shifts in growing season and water shortages, notably in SE England.

8. As well as climate change, other large-scale environmental changes are likely to have increasing importance. Agriculture and land management themselves both drive change, influencing flows of water, nutrients, carbon and the distribution of species and habitats, and in turn respond to environmental change by introducing modified systems of cropping and husbandry. The Millennium Ecosystem Assessment[4] (2005) showed how agriculture often depletes natural resources, threatening the delivery of ecosystem services[5] such as water regulation and, of course, continued food production.

9. After a period of low food prices and stable production, food prices have risen sharply recently. This has been partly driven by oil price rises, increasing use of arable crops for bioenergy, and impacts of extreme weather events on production. But the ultimate driver is an increase in global demand for agricultural products associated with increased size and wealth of human populations. These changes are raising fears of threats to global food supply that will be exacerbated by forecast changes in climate. Crop yield will be affected by environmental change resulting from predicted long-term changes that include increases in carbon dioxide, temperature and ozone and reductions in water availability. The International Assessment of Agricultural Science and Technology for Development[6] explores how knowledge needs to be harnessed to deliver the challenges of food production, poverty alleviation and sustainable development. In 2008, the UK government launched a Foresight programme in 'Land Use Futures'[7] and announced plans for a further programme in 'Food and Farming'. Such international and UK reports will be valuable in framing future research agendas within which BBSRC will need to operate.

10. As the pace of environmental change increases, research is needed to improve our knowledge of environmental change and its impacts, enable better

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[2] IPCC Fourth Assessment Report (2007) http://www.ipcc.ch/
[3] Stern report: http://www.hm-treasury.gov.uk/stern_review_final_report.htm
[4] Millennium Ecosystem Assessment: http://www.maweb.org/en/index.aspx
[5] For a definition of ecosystem services, see Glossary (Annex 3)
[6] IAASTD report: http://www.agassessment.org
[7] Foresight: http://www.foresight.gov.uk/OurWork/ActiveProjects/LandUse/LandUse.asp

prediction of how biological systems will respond, and allow better informed decisions on strategies and technologies for both adaptation and mitigation.

11. BBSRC has a key role to play as the principal UK public funder supporting research and training in the (non-medical) biological sciences. Historically, among the main sectors that BBSRC research underpins are agriculture and the food industry. Agriculture and changing land use can have undesirable environmental impacts. For example, agriculture makes a substantial contribution to greenhouse gas emissions: it is the source of 7% of total UK emissions, but 36% of methane emissions (from livestock and livestock manures) and 67% of nitrous oxide emissions (from livestock manures and artificial fertilisers)[8]. Other impacts can include diffuse water pollution and biodiversity loss[9].

12. Increasing agricultural production thus has the potential for further negative impacts, but there is also scope to mitigate undesirable environmental change in this sector (e.g. reduction in greenhouse gas emissions). At the same time, rising costs of energy and restrictions on the use of nitrogen, pesticides and waste disposal are creating new challenges to the agri-food industry. BBSRC research is required to address these complex issues and provide the necessary underpinning scientific knowledge upon which policies and practice can be based.

Scientific scope of the review

13. This review has a focus primarily on relevant areas of science within BBSRC remit (see also the next section) where there is known to be, or likely to be, an effect of climate or other environmental change. The scope of the review is deliberately broad, touching on many aspects of the BBSRC remit. It includes topics where there is potential for adaptation to, and mitigation of the impacts of, environmental change. Although agricultural systems (with their associated semi-natural ecosystems) are a significant focus of this review, BBSRC's interests are by no means restricted to an agricultural context. The report focuses on research that is expected to change technology, practices or behaviour, but the time scales of likely impacts vary greatly, and so the report covers fundamental, strategic and applied science.

14. Topics considered in the review included the following broad areas:

- the science underpinning sustainable agriculture and aquaculture, covering soil biology, land use and management (including socio-economic aspects), biodiversity conservation, and ecosystem function and service provision

- adaptation of agricultural systems, including production of crops (arable, horticultural and pasture) and livestock; also pests and pathogens of plants and animals (including zoonoses), and farm animal health and welfare

- food safety, in particular the microbiological aspects of food-borne pathogens (where the main focus of research is on the biology of the pathogen, rather than human clinical aspects that would fall with the remit of the Medical Research Council); also food spoilage

[8] Defra website: http://www.defra.gov.uk/farm/environment/climate-change
[9] Green, RE, Cornell, SJ, Scharlemann, JPW & Balmford, A (2005) Farming and the fate of wild nature. *Science* 307: 550-555

- basic studies of the responses of plants, animals and microbes to changing climate and other environmental factors, in terrestrial and marine environments; also the interactions among species; and opportunities for novel biological solutions, especially for mitigation of climate change, but also to address other environmental changes such as bioremediation of contaminated land

- biomathematics, modelling and systems biology approaches to topics in environmental change.

15. Note that **bioenergy**, while clearly relevant to the scope of the review, was the subject of a previous BBSRC strategic review[10] in 2006, and a funding initiative was launched as a result. Accordingly the current review did not revisit that topic in detail.

Remit of BBSRC

16. It is important to note that in the context of this review the remit of BBSRC primarily covers research on the responses of biological systems (including agricultural systems) to changing climate and other environmental factors and their possible adaptations to those changes. Research focused on measuring, modelling and predicting change in the Earth's environmental systems falls within the remit of the Natural Environment Research Council[11] (see also **ANNEX 2**).

17. BBSRC works closely with other research funding bodies, including NERC and the other research councils, Defra and the devolved administrations, each of which has a distinct role and remit. The funders aim to coordinate their activities wherever appropriate and, in addition to various jointly funded initiatives, mechanisms have been put in place to facilitate the funding (or co-funding) of research projects that span the scientific remit of more than one funder. It was apparent, however, that numerous respondents to the consultation were unaware of these arrangements. We address aspects of coordination with other funders in Chapter 3. While BBSRC operates alongside and in cooperation with other funders, the primary focus of this report is on research within the remit of BBSRC.

Living With Environmental Change programme

18. The UK's main funders of environmental research (research councils, government departments and other public sector funders) have joined forces in a major new partnership to address the need for research related to climate and other environmental change. Living With Environmental Change (LWEC[12]) is planned as a ten-year programme (2007 – 2017), currently under development as one of the cross-disciplinary and multi-funder programmes following the government's Comprehensive Spending Review in 2007.

19. LWEC is intended to provide decision makers with the best information to effectively manage and protect vital ecosystem services. It will improve the tools and knowledge needed to build resilience, mitigate problems, and adapt

[10] BBSRC Bioenergy review (2006): http://www.bbsrc.ac.uk/organisation/policies/reviews/scientific_areas/0603_bioenergy.html
[11] NERC: www.nerc.ac.uk
[12] LWEC programme: http://www.nerc.ac.uk/research/programmes/lwec/aims.asp

to environmental change. High-level strategic objectives for LWEC have been defined, and detailed programmes are being developed by the various funding partners. BBSRC is leading on Objective C: "*To promote human well-being, alleviate poverty and minimise waste by developing sustainable ecosystem management approaches for safe and secure food production and water supply*". BBSRC also has interests in several other LWEC objectives. It is hoped that the advice from this review will help further refine BBSRC's contribution within LWEC.

Summary information on BBSRC funding

20. As background, we provide an overview of recent BBSRC funding[13] in this area. We reiterate that the remit of BBSRC covers much research of indirect relevance to environmental change (research on the function and responses of biological systems) but in general BBSRC does not support research directly on environmental change as such (biophysical mechanisms of global change), nor on societal drivers of environmental change (see also paragraph 16).

Table 1: BBSRC funding for research relevant to environmental change

Environmental change includes research involving the responses of biological systems (including agricultural systems) to climate and other environmental factors and their possible adaptations to it. Environmental factors include: temperature (high and low); gases (e.g. ozone, carbon dioxide, methane, oxides of nitrogen); water (drought and flooding); wind (e.g. crop lodging); sunlight; and salinity. Pollution of the land, water courses or atmosphere is also considered an environmental change. Research relating to environmental change may include the effects of the aforementioned factors on: the incidence of diseases and pests (of livestock or crops); crop and livestock production (including animal welfare); and land use strategies.

Research may also include the impact of these environmental factors on biodiversity, soils and the aquatic environment. Phenology (that is, the study of organisms as affected by climate, especially dates of seasonal phenomena such as migration or opening of flowers) is also included. Research of relevance to environmental change may relate to the impacts of the environmental change and/or ways in which organisms/systems adapt to or mitigate the effects of those impacts.

Estimated spend on research relevant to environmental change (£M)

	2006/07	**2007/08**	**2008/09 (forecast)**
funding to universities, etc	£4.0	£4.1	£4.9
funding to BBSRC institutes	£7.3	£7.5	£10.4
Total	**£11.3**	**£11.6**	**£15.3**

21. Among its range of funding schemes, BBSRC has in place several that are directly in support of knowledge transfer[14]. Over many years BBSRC (with other government sponsors) has co-funded research with industry through LINK programmes. Agriculture and its related industries has been one of the main industrial sectors supported through LINK, and partners have included the agricultural levy bodies. Further mechanisms to fund research in support of

[13] Further information on BBSRC funding: http://www.bbsrc.ac.uk/organisation/spending
To search the BBSRC portfolio of funded research: http://www.bbsrc.ac.uk/science/grants
[14] BBSRC knowledge transfer schemes: http://www.bbsrc.ac.uk/business

industry include the Industrial Partnership Awards scheme (promoting co-funding by industry of individual responsive mode grants), the recently-established industry clubs in several sectors including the food industry (with industry contributing to a common pot of funding for industrially-relevant projects), and the Follow-on Fund (for proof of concept at an early stage of turning research outputs into a commercial proposition).

Summary information on other funders

22. In addition to BBSRC, the other main UK public funders of (biological) research relating to environmental change are NERC, Defra, the Scottish Government, and the Environment Agency. Further information is provided at **ANNEX 2**.

Strengths and weaknesses of BBSRC-funded research

23. The responses from Directors of BBSRC Institutes, BBSRC Research Committee Chairs and the responses obtained during the consultation exercise were helpful in identifying perceived areas of strength and weakness in the current portfolio of BBSRC research, and more widely in UK research activity. These are summarised in the following paragraphs, along with areas identified as opportunities.

24. Overarching strengths

- The BBSRC science portfolio enjoys an international reputation in the molecular sciences, especially in the areas of gene and protein function. This position has been the result of recent and past investment by BBSRC and other funders. While the primary purpose of this investment was not to tackle environmental questions, the knowledge and skills now available mean that BBSRC is in an excellent position to develop innovative solutions to some of the problems and to seize opportunities that will arise as a result of environment change.

- Building on its earlier investments in molecular and genomic sciences, BBSRC is playing a leading role in the emerging science of systems biology[15]. BBSRC has established six major UK research centres, with further funding through large grants and networks, collaborative research with industry, international partnerships, focused postdoctoral training and funding for mathematical resources.

- BBSRC's portfolio in soil science, sustainable agriculture, animal and plant disease management and landscape-scale processes is world class and is built on a long tradition beginning with the classical experiments established at Rothamsted over 150 years ago.

- The BBSRC-sponsored institutes provide world-class facilities and capabilities for research, collaboration, demonstration and knowledge transfer. Facilities include world-renowned long-term field experiments and high-containment laboratories for animal disease research.

25. Opportunities

- A major opportunity exists to use the expertise of BBSRC-funded scientists to develop innovative approaches to managing crops, farm animals and the

[15] For a definition of systems biology, see Glossary (Annex 3)

agricultural landscape for economic, social and environmental benefits in the face of environmental change.

- A further opportunity exists to develop expertise in applying integrative, systems biology approaches to investigating these questions. Specifically, opportunities exist for conducting studies that seek to integrate and scale up information from the molecular level, through cells, tissues and organisms to populations, communities and ecosystems.

- Other areas of science are emerging that offer important new opportunities to BBSRC, taking advantage of developments in molecular biology, computing and environmental sensing.

- Environmental change is creating opportunities to work in partnership with industry and with other disciplines to develop new products and processes, including new crop varieties, new information and decision support systems, biomarkers and sensors.

- There are opportunities to work closely with other government funders in jointly addressing the emerging issues associated with environmental change both in the UK and overseas.

26. Weaknesses / barriers / threats

- Lack of critical mass and training in key translational skills including plant breeding, whole plant biology and taxonomy.

- Reduction and fragmentation of parts of the research base; decline in some facilities especially in agriculture; lack of strong agrichemical industry in the UK.

- Public mistrust of some technological innovations that may prove valuable, not least genetic modification (GM). Technologies such as GM have the potential to provide solutions to certain problems that will arise as a result of climate and other environmental change. Increasing public attention to the problems of climate change may offer an opportunity for productive public debate in relation to new technologies.

- Poorly understood boundaries between BBSRC, NERC and Defra in their funding interests in research in agricultural systems lead to the potential for duplication of some research, with other work falling through the cracks. Similar interface issues arise with other funders too, such as between BBSRC and MRC, or with ESRC.

- Lack of career incentives for individuals to move into translational research or to collaborate with applied scientists (a broader issue not limited to environmental change research).

27. We conclude that there are major opportunities for BBSRC to contribute towards addressing problems related to environmental change, including via the Living with Environmental Change programme. Some of these opportunities will be specific to BBSRC while others should be carried out in partnership with other government funders. We turn to addressing these aspects in Chapter 2 (in relation to scientific opportunities) and Chapter 3 for implementation and delivery.

CHAPTER 2: SCIENTIFIC PRIORITIES

28. In this Chapter we turn to recommendations on specific topics that should be adopted as priorities for future BBSRC research.

29. Initial discussion by the panel led us to propose a series of potential priority topics. These were included in the consultation document and have been amended in light of some of the many helpful responses submitted. The list is followed by a section on over-arching issues of relevance to BBSRC engagement with research in environmental change.

PRIORITIES FOR RESEARCH

30. The panel assessed where future BBSRC-funded research can make most impact in addressing key problems in environmental change. As set out in Chapter 1, much research across the wide remit of BBSRC is relevant to environmental change. We concluded, however, that the topics in which BBSRC will be best placed to contribute will be primarily in relation to agriculture and food production.

31. An important overall strategic objective in setting the priorities that follow is that BBSRC should take a leading position in providing the science to underpin agriculture that is not only productive but that also supplies other ecosystem services (e.g. nutrients, water, biodiversity) and in ways that are resilient to the impacts of climate and other environmental change. Research must support the delivery of multifunctional land management in agricultural systems.

Recommendation 1: In relation to environmental change, BBSRC should adopt as leading priorities research that will:

A. Predict the incidence of those pests and diseases of farm animals (including zoonoses) and crop plants that are likely to increase as a result of environmental change, and develop measures to combat their spread and mitigate their impact

B. Develop new varieties of crops and livestock, and novel practices, systems and strategies to enhance the efficiency of agricultural production sustainably in response to environmental change

C. Explore new opportunities to mitigate environmental change through the emerging science of biogeochemical engineering

D. Improve the ability to predict and manage the effects of environmental change on soil systems, ecosystem function and services, and biodiversity conservation in agricultural and associated landscapes

32. Further details of these priorities is provided in the following sections, followed by some cross-cutting issues. In reflection of the breadth of research covered within the scope of this review, the priorities represent a mixture of basic underpinning research and more strategic or applied topics. It is appropriate that BBSRC supports research across the range of its remit and covering the spectrum from basic to applied work.

Priorities in detail

A. Predict the incidence of those pests and diseases of farm animals (including zoonoses) and crop plants that are likely to increase as a result of environmental change, and develop measures to combat their spread and mitigate their impact

33. BBSRC funds a large amount of research on diseases, pathogens and pests of farmed animals and crops, although only a small proportion of that investment is currently focused on the effects of climate or other environmental change. Threats from new or emerging pests and diseases are expected to increase as a result of climate change, coupled with increased trade and international movements of people, plants and animals. Of particular concern are newly emerging zoonoses that may arise, threatening human health as well as livestock production. In addition, research is needed on the effects of environmental change on the vectors (insects etc) that spread plant and animal diseases (since their distribution is liable to alter with changing climate – e.g., the midges that carry bluetongue virus); also on beneficial insects, notably bees. Weeds may also change in distribution or severity under changing environmental conditions: the emergence of resistance to herbicides remains a challenge.

34. Future priorities for BBSRC research in relation to environmental change in this area should be to:

- Integrate empirical and predictive research on the occurrence and impact of pests and pathogens of crops and livestock, in order to manage their biological and socio-economic effects. Research will cover host-pathogen interactions in response to environmental factors, singly and in combination. Crops are subject to simultaneous attacks by both pests and pathogens, and so the interacting effects (both synergistic and antagonistic) of these threats should be considered – defence against one may influence resistance against the other.

- Develop new theories and models that include environmental change data to predict the incidence and virulence of pests and diseases of crops and livestock (including disease vectors, zoonoses, also weeds). Models should include high levels of spatio-temporal information, as well as rapid data acquisition to allow early intervention during disease episodes. In parallel with this work it is necessary to continue development of biomarkers and other sentinel technologies. Collaborative research will be needed across academic disciplines and with industry, and should make full use of new technologies including biotechnology.

B. Develop new varieties of crops and livestock, and novel practices, systems and strategies to enhance the efficiency of agricultural production sustainably in response to environmental change

35. This priority covers crops (primarily food, but also including feed and non-food crops), livestock and aquaculture, and agricultural practices. Increasing demand from a growing population and increasing affluence, coupled with evidence for downward trends in global stocks of staple crops, suggests that the world's future food supply will be at risk. Long-term research is needed now to reduce that risk and help ensure future food security.

Crops

36. Crop yield will be affected by environmental change resulting from predicted long-term changes including increases in carbon dioxide, temperature and ozone and reductions in water availability. The incidence of short term non-seasonal climatic episodes such as flooding is also set to increase. Effort is needed to generate crop cultivars adapted to future climatic conditions and the evolving farming systems in which they will be adopted. They must meet the needs of farmers, the food chain and consumers without degrading the capacity for future and making best use of energy, nutrients, water and other resources. International effort should focus on the most important crops worldwide: maize, wheat, rice and soybean. Research is also needed for other food and fodder crops relevant for UK agriculture.

37. Note: this review did not focus on **bioenergy** since that was the subject of a previous BBSRC review and new research programmes are being instigated. But we reaffirm the need to address issues such as: food versus biofuel production; the need for research on second generation biofuel technologies, and introduction of new bioenergy crops and cultivars adapted to the future climate.

38. Specific priorities for crop research should be:

    - Develop and test theories and models to predict at the field level the effects of combinations of changes in carbon dioxide, temperature, ozone and water availability on crop yields and nutrition. Research should include effects of soil and water management practices.

    - Exploit knowledge gained from the study of model species to adapt new crop cultivars that use water more efficiently, tolerate flooding (raised water tables), salinity, high and low temperatures and are more resistant to wind and water damage and to pests and diseases (see also section Priority A). Approaches should exploit both conventional plant breeding (coupled with advanced techniques emerging from genomics) and genetic modification technologies. A key priority will be to maintain or increase crop yields while increasing tolerance / resource efficiency.

Livestock

39. Research is needed on adapting livestock production practices to reduce environmental impact, in particular to reduce greenhouse gas production. This will entail integrated approaches including basic research on animal physiology as well as breeding, nutritional and management practices, and involving both modelling and experimentation. Technique development may be required, e.g. robust techniques to measure/predict methane production at an individual animal level. Research will also be needed to reduce the impacts of environmental change, for example addressing animal welfare implications of increased temperature.

40. Aquaculture forms a significant component of food production, and dietary advice is that the UK population overall should eat more fish. But aquaculture systems (both marine and freshwater) are likely to face challenges arising from environmental change, such as changes in biodiversity or population abundance of exploited species or microflora, new occurrences or increased incidence of pests and diseases (including potential new zoonoses) and

increased toxin production. Research on aquaculture systems will be needed to address these challenges, and should include the effects of environmental change (for instance temperature, water acidification) on food production and the associated food supply chains, including their microbiological safety.

Agricultural practice

41. There is considerable scope for the agricultural sector to contribute to adaptation to and amelioration of environmental change through refinements in agricultural practice. Changes in practice provide the route to implement findings emerging from research on other topics. Research should utilise developments in biological and engineering technology to develop productive agricultural systems that have a low environmental impact. This will include systems that have low energy usage, reduced greenhouse gas emissions and make efficient and effective use of chemical and water inputs. Approaches will include improved soil management to reduce erosion and emission of greenhouse gases, using remote sensing to map areas where fertiliser is required and changing livestock waste management systems to reduce pollution.

42. Future priorities for BBSRC research in relation to environmental change in this area should be to:

- Develop strategies to increase carbon sequestration and reduce emissions of carbon dioxide and methane (also N oxides). Research is also needed to help ensure that water is used more economically (through improving tillage and irrigation, as well as crop breeding – see above) and water quality is improved (reduction in pesticide, fertiliser and farm waste run-off).

- Develop novel pesticides and plant growth enhancers designed to work under predicted climatic conditions. Continue to develop and evaluate precision agriculture and biological control (including gene technology) strategies.

- Develop methods to control crop and livestock pests under predicted climate conditions, without increasing potential harmful effects on non-target organisms. Research should take account of pressures to reduce harmful impacts of chemical inputs to the environment. Methods may include chemical pesticides with new modes of action, new formulations and application technology, conventional plant breeding, chemical manipulation of plant physiology, genetic modification of crops, genetic modification of pests or plant disease vectors, semiochemicals, biological control, cropping combinations and rotations. In addition, research to extend the useful life of existing control methods, including delaying the evolution of pest resistance to pesticides, is important.

- Develop ways of reducing wastage in the food chain (through reduced spoilage and more efficient processing). There are clear opportunities for collaborative research with industry in this area.

C. Explore new opportunities to mitigate environmental change through the emerging science of biogeochemical engineering

43. Biogeochemical engineering exploits discoveries in molecular biogeochemistry to ameliorate global change. It can be seen as a sub-discipline of geo-engineering (or geo-scale engineering), which may be defined as the large-

scale manipulation of environmental systems in order to make worldwide changes for human benefit, in particular to counteract the undesirable effects of climate change[16]. Such ideas are, by their large-scale nature, prone to unpredictability and are likely to be controversial. Among the wide range of possible technologies, those involving managed ecosystems, particularly annual crops and grasslands, may offer an attractive, safe (since they can be readily stopped) and relatively rapid vehicle for interventions.

44. By further basic research in model systems and the transfer of this to agricultural and forest organisms, new mitigation options are opened. Each potential modification should be assessed in the context of global circulation models to determine cost/benefit. In the wider context this modelling could provide a basis for developing systems for crediting landowners for implementation of these new mitigation options. Promising areas for BBSRC research include:

- Genotypes of our major food and forestry crops show wide variation in leaf reflectivity. Crops cover some 10% of the land surface and managed ecosystems such as production forests a much greater portion. A modest increase in albedo of this surface would produce a significant cooling effect.

- Soil currently contains twice the carbon of the atmosphere, and so a small increase in the soil carbon pool could provide a substantial offset. Modification of crop litter to slow decomposition would increase carbon accumulation in agricultural soils.

- Identify genetic and dietary modifications that could decrease methane and nitrous oxide emissions from animal production (see also Livestock, under priority B).

- Ozone in the troposphere is the third most important greenhouse gas after carbon dioxide and methane. Volatile organic carbons (VOCs) such as isoprene emitted from vegetation catalyse ozone formation. Decreasing VOC emissions from the plants of managed ecosystems, e.g. by exploiting genetic variation or through interventions in the biosynthetic pathways, would help counteract the current upward trend in global ozone.

45. The BBSRC research community should thoroughly engage with the opportunities provided in the emerging discipline of biogeochemical engineering, as they already have the expertise in biology and biotechnology to allow rapid progress in this area. Research should incorporate consideration of social and economic factors that may affect the success and uptake of potential future technologies.

D. Improve the ability to predict and manage the effects of environmental change on soil systems, ecosystem function and services, and biodiversity conservation in agricultural and associated landscapes

46. Ecosystem services are the functions of ecosystems that are valued by humans. These include food production, management of landscapes, regulation of water flow and quality, support of biodiversity at genetic, species and ecosystem scales, and also cultural heritage. There is a need to quantify the services currently delivered by managed land in the UK and elsewhere, and

[16] See for example, Philosophical Transactions of the Royal Society Special edition on Geoengineering (Sep 2008) http://royalsociety.org/news.asp?year=&id=7983

this is particularly important for regions that are vulnerable to change and/or of high value. This approach can help communicate the choices and trade-offs that are implicit in any proposed land use change. Both systems and spatially explicit models can be used to identify the potential impact of future land use scenarios on the provision of ecosystem services.

47. Future priorities for BBSRC research in relation to environmental change in this area should be:

- The development of improved models and theories of the response of managed ecosystems (agricultural and associated semi-natural systems) to environmental change. Research should build on strengths in modelling, experimentation and existing data resources at a range of spatial scales (including microbial, field, landscape and regional) to address the basis and maintenance of population abundance and community richness in changing agricultural systems, leading to improved management practices for enhancing their resilience.

- Because environmental change will impact on land use strategies and vice versa, research is needed to support development of integrated, rather than sectoral, land use policies. It will be necessary to increase the availability of sites for monitoring and experimental study. Integration with NERC and ESRC activities in this area will be essential: research should build on experience from the Rural Economy and Land Use (RELU) cross-Research Council programme to study the interactions of social and economic factors with management for biodiversity in agricultural systems. It may be appropriate to share some facilities at the UK and European levels.

- There is a need to quantify the contribution of soils in agricultural and associated semi-natural systems in supporting primary production, regulation of climate change, nutrient cycling and water regulation (i.e. ecosystem services). This will require the development of system-based approaches that quantify and predict how alterations in soil microbial and faunal diversity impact carbon sequestration and biogeochemical cycles. This work will offer opportunities to develop theoretical frameworks to integrate biological, chemical and physical aspects of the carbon cycle both above and below-ground and across various temporal and spatial scales. New opportunities are also arising in environmental sensing and manipulation to develop predictive frameworks to enhance the management of these processes.

Immediate priority

48. Among the topics highlighted above, the most urgent priority, in our view, is research on pests and diseases of crops and livestock, since the threat of new disease incursions has the potential for immediate and severe economic and social impact (e.g., foot and mouth disease outbreaks) and it is a topic with existing BBSRC research strengths across its institutes and in the universities.

49. The BBSRC Delivery Plan[17] (2008-2011) set out the intention to "commit £22M to increase research relevant to the LWEC programme, primarily through existing strengths in sustainable agriculture and animal health in our institutes", and to "fund new research to develop predictive models of how farming systems respond to environmental change and new farming practices, so that

[17] BBSRC Delivery Plan (2008-2011): http://www.bbsrc.ac.uk/publications/policy/bbsrc_delivery_plan.html

knowledge about effects on food production, livestock diseases, wildlife and land use can inform national preparedness and minimise economic and social costs."

50. Accordingly, within this framework, we advocate a new funding initiative around **priority A** (above) that would build research capacity by integrating expertise on both crop and livestock diseases while also addressing socio-economic impacts. Research should integrate experimental work on how environmental factors affect mechanisms of infection, transmission, host-pathogen interactions and epidemiology, using systems-based approaches and predictive modelling across a range of scales, coupled with relevant socio-economic work on disease management practices. The initiative should build on the experience of the RELU programme, working in partnership with other funders, and could form a central component of the LWEC programme.

OVER-ARCHING ISSUES

Modelling approaches

51. An emerging issue that fits well with the BBSRC vision[18] "towards a predictive biology" is the desirability of including a mathematical modelling element in future work. Other funding agencies already invest heavily in modelling and it will be essential to coordinate effectively with the other funders to build capacity and ensure cross-compatibility of models in order to deliver maximum benefit from this approach. Suitable models need to be made widely available, and should use recognised international standards for exchange and inter-operability. Ensuring that a systems-based approach is firmly embedded in BBSRC-funded research will ensure that quantitative data sets are used effectively in the production of models incorporating strong predictive elements. Accordingly, for all priorities, the review panel wishes to encourage, wherever appropriate, multidisciplinary and/or systems biology/ mathematical modelling approaches to studying, predicting and mitigating the effects of environmental change.

52. Such studies will need to be complemented by empirical, experimental, systems-based research. Integration of different approaches will improve our knowledge of, and ability to predict, how biological systems – and especially agricultural systems – respond to environmental change, to identify indicators that give early warning of major changes in the agri-ecosystem, and how to maintain their sustainability in the long term.

Systems biology

53. BBSRC's commitment to the encouragement of systems biology approaches has thus far been most apparent at the intra-organism levels of biological organisation. It seems increasingly clear that the scientific challenges posed by environmental change (and climate change in particular) demand the integration of concepts, methods and models for the study of biological systems across scales from molecular to population and ecosystem levels. A systems-based approach is necessary to underpin the development of increasingly productive agriculture as part of land use strategies that will maintain long-term stewardship of other ecosystem services such as water, soils and biodiversity. Research communities that are currently largely separate will need to collaborate and integrate.

[18] BBSRC Ten-Year Vision, 2003-2013: http://www.bbsrc.ac.uk/publications/policy/bbsrc_vision.html

International dimensions

54. The challenges of environmental change, and the research required to address those challenges, clearly have a global dimension. Concerns over food security are increasing, energy prices are rising, carbon dioxide is set to rise worldwide, and improving water use efficiency is already a primary objective in other countries (e.g. Australia and China). Accordingly it is necessary for BBSRC to be aware of and, wherever appropriate, to participate in international research programmes and to coordinate activities with sister funding agencies overseas, maximising synergy and avoiding duplication.

CHAPTER 3: DELIVERY MECHANISMS

55. In this chapter we consider issues around the delivery of BBSRC research relevant to environmental change and make recommendations that will enhance the implementation of research priorities, boost national capability and improve coordination among research funders.

Coordination across funders

56. We welcome the establishment of the LWEC programme as a major initiative across not only the Research Councils but more widely across government (including the devolved administrations) and other stakeholders (see also paragraph 18). We further welcome and endorse BBSRC's involvement in the LWEC programme and other cross-funder activities. Examples include the Environment Research Funders' Forum (ERFF) and its recently launched Environmental Observation Framework[19]. Coordination and close working among research funders will be essential if we are to address effectively the major challenges ahead in relation to environmental change.

57. Recent examples of initiatives developed with and co-funded by other UK agencies include the Rural Economy and Land Use (RELU) programme[20], which broke new ground in forging collaborations of biological and environmental science with social and economic research. More recently the initiatives in Sustainable Agriculture Research for International Development (SARID[21]) and Combating Infectious Diseases of Livestock for International Development (CIDLID[22]) were developed with co-funding by DfID and promoted new collaborations between UK researchers and those in developing countries (who would not normally be eligible for UK research council funding). We fully endorse the need (expressed in several responses to the consultation) to build on these innovative programmes (see also below - Interdisciplinary approaches) and would see the LWEC programme as a suitable framework.

58. We recognise that LWEC is work in progress, but we have concerns that LWEC Objective C (on which BBSRC is leading – see paragraph 19) is written so broadly as to make it hard to envisage how it might be taken forward. Yet there is a clear opportunity for BBSRC to establish a leading role and ensure that basic and strategic research within BBSRC's remit on food, agriculture and the managed landscape are well represented within LWEC. Addressing the key questions in environmental change will require both short- and longer-term investment and BBSRC must look ahead beyond LWEC.

Recommendation 2: BBSRC should develop a leading position with respect to food, agriculture and the managed landscape within the LWEC programme in view of its importance as a major cross-Council, and multi-stakeholder, programme. In the longer term, BBSRC should prioritise funds from the next spending review and beyond for sustained investment in research to manage the impacts of environmental change. This reflects the importance, magnitude and long-term nature of the challenges.

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[19] Environmental Observation Framework: http://www.erff.org.uk/activities/uk-eof.aspx
[20] RELU programme: http://www.relu.ac.uk/
[21] SARID initiative: http://www.bbsrc.ac.uk/media/releases/2008/080221_sarid.html
[22] CIDLID initiative: http://www.bbsrc.ac.uk/funding/opportunities/2008/combating_infectious_diseases_livestock.html

BBSRC institutes

59. BBSRC sponsors some of the key UK research institutes in areas relevant to environmental change, including the Institute for Animal Health, Institute of Food Research, John Innes Centre, Rothamsted Research and North Wyke Research. Research institutes are able to sustain mission-led strategic and multidisciplinary programmes with a longer-term perspective than is typically seen in the university sector, and in some cases they host facilities that are unique in the UK and essential to deliver the required research outcomes (eg, long-term field experiments with associated data sets, and disease containment facilities for large animals).

60. The institutes are well placed to take a leading role in research relating to environmental change, particularly in the agricultural context, and we commend the efforts already made. We would support further collaborations with other institutes (BBSRC-sponsored and those supported by other research councils or government departments) as well as universities, industry and other relevant partners. These could include non-governmental organisations, especially those which are research-based and/or have land resources that could complement those of institutes in providing opportunities for research at larger ecological scales. From the consultation, we were not made aware of any particular barriers against collaborations with universities or others, but it is essential that Council encourages and facilitates this role for the institutes and seeks to minimise any barriers that might hinder such collaborations.

61. We welcome the move by BBSRC to replace institute core funding with strategic programme grants, especially those that are cross-institute programmes (currently soil science and cereal genetics) as these provide a framework for more integrated approaches and collaborations that should make better use of available expertise and resources across the institutes. Additional cross-institute programmes in relation to environmental change, for example in animal disease/zoonoses/food-borne pathogens, and in plant disease (to include molecular mechanisms of infection and resistance, epidemiology and disease management) could be valuable and Council should encourage the institutes to explore this.

62. We recommended above that BBSRC should take the leading role in agricultural and food research under the LWEC programme and beyond. As a part of that role, we wish to encourage the development of national facilities that would be available for collaboration and training across the research community. The valuable current facilities at BBSRC institutes (eg, long-term field experiments, disease containment facilities) are an obvious basis on which to build. Their development as national facilities for research relevant to environmental change would promote new collaborations and the wider use of the institutes' infrastructure as well as more extensive sharing of their existing data sets, collections and other resources. The institutes should be encouraged to allocate funds towards such developments, and Council should consider establishing specific funding schemes to promote collaborative research involving the institutes.

63. We welcome the joint plans (although they are yet to be finalised) by BBSRC and Defra to redevelop the Pirbright Laboratory of the Institute for Animal Health as a world-class facility for animal disease research, and the further

recommendation by the Beringer review[23] that it should be positioned as a new national centre. We would encourage Council to explore, with relevant funding partners, the possibility of BBSRC institutes forming the basis for national facilities (possibly a national centre) as a focus for research relevant to environmental change in the agricultural context.

64. We address further issues in relation to the BBSRC institutes in the sections below on translational research and facilities.

Recommendation 3: BBSRC should give every support to its institutes in engaging fully with research relevant to environmental change and especially addressing the priorities we have listed. Consideration should be given to further cross-institute programmes or other mechanisms that foster productive collaborations between institutes. BBSRC should ensure that there are no barriers that would prevent its institutes working together or in partnership with other research institutes, universities, industry or non-governmental organisations.

Recommendation 4: In taking the lead in agricultural and food research – for example under the LWEC programme – BBSRC should develop national facilities located at its institutes that can be accessed more widely by researchers working in the context of environmental change.

Innovation, translational research and partnership with industry

65. Many responses to the consultation gave strong support for collaborative research with industry and welcomed co-funding in the area of environmental change. Others were more cautious and perceived difficulties, for example from different time scales of research interests (industry tending to be more short-term), or in topics too basic in nature to stimulate immediate interest from industry.

66. In our view, combating the deleterious effects of environmental change and exploiting potential opportunities arising from changes in climate will require BBSRC to work closely with industry stakeholders not only to develop novel techniques and approaches but also (and importantly) to stimulate translational research (e.g., to take lessons learnt from model organisms or systems through to application in agriculturally relevant species and practices). Accordingly there is a need for innovation across the spectrum of basic, strategic and applied research, coupled with the establishment of effective partnerships with industry and other end users.

67. Basic research is often the source of innovation, ultimately leading to new products or processes. The most valuable research to industry may result from projects supported through the responsive mode where innovative ideas are generated without any preconceived applied purpose. Industry does not necessarily need researchers to concentrate on product development – that is a role for industry itself – but it certainly needs the generation of fundamental knowledge.

68. A further important point is that there is no single readily-identifiable industrial sector for engagement; rather, environmental change is widely pervasive with

[23] Beringer review: http://www.bbsrc.ac.uk/organisation/policies/reviews/operational/0804_iah_governance.html

potential impact across all sectors, but in many different ways. Therefore a variety of routes for interactions and mechanisms for knowledge transfer from research to end users will be needed.

69. Nonetheless, with the increasing emphasis across government and the Research Councils on demonstrating the economic and social impact of research, it is clearly appropriate for BBSRC to support research relevant to the needs of industry and other end-users. We welcome the establishment of the Technology Strategy Board and urge BBSRC to engage fully with it to develop mechanisms for knowledge transfer and translation relevant to agriculture and environmental change more widely, to complement the existing Environmental Knowledge Transfer Network[24].

70. One mechanism to promote knowledge transfer could be to establish networks that bring together researchers (from different relevant fields) with industry as well as research funders and policy makers. Networks can be valuable in building capacity in otherwise fragmented topics. Another approach to boost connectivity between industry, research and translation is through the use of Research Technology Clubs (RTC). In an RTC companies contribute collectively to a common pot with BBSRC, identify generic research challenges which offer the opportunity for both high-quality research and industrial applicability, and seek bids from universities and institutes in those areas. BBSRC should consider whether such approaches could help to integrate and focus research activity on the needs of end users of environmental change research.

71. Many of the issues highlighted in the previous BBSRC review of Crop Science[25] remain pertinent in the wider context of environmental change. There is a clear need for improved translation of the UK's excellent basic research through to new crops and other products and processes. In particular, that report highlighted (recommendation 14 of the Crop Science report) the opportunity for BBSRC to lead in establishing a national plant breeding initiative that would promote public-good plant breeding. This is yet to be tackled adequately, and weakness in public-good plant breeding remains a barrier to delivering some of the new crops that will be needed in response to environmental change.

72. We consider that there is also an issue in translation of new agricultural systems and processes that might help to address environmental change. ADAS used to have a key role but this is now more limited. We are not suggesting that BBSRC institutes step into this gap, but they are nevertheless well placed (as existing centres of excellence with good connections with relevant industry, the training sector and other end-users) to make even more impact through boosting translational activities.

73. We acknowledge that institutes are already active in translation of research into practice. But, given the increasing emphasis on economic impact and the importance of environmental change research, Council should consider whether institutes should now be going even further, and if so how it can help them to do so. The institutes have been very successful in attracting competitive funding from the Public Sector Research Exploitation Fund (broadly equivalent to the Higher Education Innovation Fund) but the amount of money available is relatively small and Council should ensure that principal

[24] Environmental Knowledge Transfer Network: http://www.environmental-ktn.com
[25] http://www.bbsrc.ac.uk/organisation/policies/reviews/scientific%5Fareas/0404_crop_science.html

investigators at BBSRC institutes have the right career incentives and drivers for more translation-like research.

Recommendation 5: To maximise economic and social impact BBSRC should increase the effectiveness of translation and exploitation of research relevant to environmental change through a number of mechanisms, in particular by:

- ensuring that the topic is highlighted as a priority throughout its various schemes to promote partnerships with industry;
- working with the Technology Strategy Board and other funding partners to facilitate innovation and knowledge transfer;
- exploiting the existing resource of its relevant institutes by ensuring adequate funding and appropriate career incentives / recognition for translational activities.

Facilities and collaboration

74. It is clear that there is already much work in the area of environmental change in the UK and abroad supported by a variety of agencies. Many of these have established experimental sites and have gathered data relevant to environmental change for many years; there is scope to add new methods of sensing and it may prove valuable to link with atmospheric and hydrological monitoring networks. Ensuring that there is widespread access to both experimental sites and data sets is required to maximise progress. We strongly welcome the implementation of the BBSRC data sharing policy and recognise the need for ongoing investment in effective archiving of data. Expanding international collaborative efforts will help to ensure that BBSRC science continues to be relevant at the global scale.

75. Both the forthcoming BBSRC/HEFCE Study of Land-Based Facilities and Resources and the recently instigated ERFF Environment Observation Framework (EOF) are expected to provide valuable surveys and other background information upon which BBSRC and other funders can base strategic decisions on the most appropriate investment in facilities. We addressed earlier the issue of making relevant facilities at the BBSRC institutes more widely accessible.

Recommendation 6: BBSRC should work with other funders in the UK and overseas to promote awareness of, availability of, and access to suitable research resources to address questions in environmental change. In particular, BBSRC should seek to be a partner in suitable international programmes sharing access to experimental sites, facilities and data. The Council should ensure that funding mechanisms are available to support UK researchers in international collaborations specifically in relation to environmental change.

Interdisciplinary approaches

76. Numerous respondents to the consultation identified fragmentation of research and lack of communication among different research communities as barriers to progress. The scale and complexity of some (but not all) of the problems and research questions in environmental change mean that they cannot be answered by small-scale single-discipline research projects. For problems

such as these, interdisciplinary approaches are needed to integrate across disparate fields, including:

- integration across scales of biological systems, from genes to organisms, farms and landscapes, ultimately to the globe
- incorporating theoretical biology/ statistics / systems modelling / experimental platforms / monitoring programmes to allow researchers in different disciplines to develop and validate modelling approaches
- problem-based research that develops collaborations between biologists and researchers from other disciplines including the physical sciences (notably climatology), mathematics and engineering, also human health, economics and social science

77. We welcome BBSRC's move towards longer and/or larger grants as one means to promote interdisciplinary approaches, and would encourage the research community to take up this available mechanism and propose ambitious projects addressing key issues in relation to environmental change.

78. We recognise, however, that it would not be appropriate for all research to be carried out as large multidisciplinary projects. Rather, we favour a plurality of funding mechanisms that supports projects in the format most appropriate to address the research question being posed. It is important that funding committees remain receptive to a variety of types and size / duration of proposals.

79. We noted above how the cross-funder Rural Economy and Land Use (RELU) programme aimed to integrate socio-economic considerations into biological and environmental research, and this is an approach we commend for future research related to environmental change. Experience from RELU illustrated that truly interdisciplinary work is possible but takes considerable investment of time and effort to build integrated teams.

Recommendation 7: BBSRC should work with other funders to promote interdisciplinary research approaches to problems in environmental change, and in particular should build on the previous cross-Council programme Rural Economy and Land Use (RELU) in order to embed more thoroughly the consideration of social and economic aspects in biological and related research.

Training and skills

80. Science depends on the continued supply of researchers with skills and expertise in relevant topics. Areas of skills shortages identified by the panel and/or in responses to the consultation included capacity in trained agricultural scientists, agronomists and agricultural modellers; also in animal disease research (including vector biology), taxonomy, soil science, plant breeding and plant physiology. The proposals in this report rely on the availability of people with new skill sets in modelling, environmental informatics, analytical and "omics" techniques. There is a continuing need to ensure that biologists are suitably trained in mathematics, including statistics.

81. We note, however, that reported shortages in particular disciplines are not necessarily specific to environmental change research but will apply more widely across those topics. Furthermore, issues of shortages tend to be

complex, with problems potentially arising in both supply and demand. Efforts to boost skills in a particular topic by providing additional training places may be thwarted if students are unwilling to take up those places (as several respondents reported) or if there are only limited employment opportunities for those emerging from a course. A shift in recent years in student numbers away from biology (and especially agriculturally relevant courses) towards biomedical topics was reported.

82. Many of the training and career development issues identified in the BBSRC Crop Science Review (2004) remain pertinent, as do the various possible measures proposed to address shortages, and BBSRC should keep its provision of training under regular review. The Environment Research Funders' Forum (ERFF) is currently undertaking a Skills Needs Review[26], whose output is intended to provide a more comprehensive survey of needs across environmental research. This should provide important baseline information from which BBSRC and other funders can develop suitable plans to meet the skills needs.

83. We welcome the highlighting of environmental change as one of the topics for BBSRC targeted studentships (announced in 2008) but recognise that such measures can provide only small increases in the number of trained researchers. Masters-level courses can be useful as a fairly rapid means to boost numbers in selected topics, and we would encourage universities and research institutes to consider their provision. Courses developed in association with relevant industrial partners have proved valuable in other fields in meeting identified needs (e.g., with the pharmaceuticals sector).

Recommendation 8: Informed by this review and the forthcoming Skills Needs Review for the Environment Research Funders' Forum (ERFF), BBSRC should support and promote the provision of trained researchers in key topics within its remit that are needed to address questions relating to environmental change. Provision could include taught Masters courses, some of which could be developed in collaboration with BBSRC Institutes and/or industrial partners.

Public and stakeholder engagement

84. BBSRC already engages broadly with the public and other stakeholders through the media, websites, discussions, Science and Society events and similar, and we strongly endorse such activities. There is, however, a need for additional engagement for research related to agriculture and environmental change, which is an area of increasing public interest. As noted under weaknesses, etc in Chapter 1 (paragraph 26), the lack of public acceptability of genetic modification (GM) represents a serious obstacle to introducing potentially beneficial new crops and products. Technologies such as GM have the potential to offer solutions to some of the problems arising in environmental change. Demonstration of benefits to the environment and the wider public good may provide a fruitful basis for public debate on GM and other technologies. Funding initiatives developed under LWEC should include appropriate science-in-society activities.

Recommendation 9: BBSRC should engage wherever practicable with the public and other stakeholders on topics relating to environmental change. In particular, BBSRC should strongly encourage all holders of grants relevant to

[26] ERFF Skills Needs Review: http://www.erff.org.uk/activtiies/skills.aspx

environmental change and BBSRC institutes carrying out research in this area to participate in public engagement activities. The lack of public acceptability of technologies such as genetic modification represents a barrier to addressing the challenges of environmental change and BBSRC must work with other stakeholders to promote effective dialogue.

ANNEX 1

PANEL MEMBERSHIP AND TERMS OF REFERENCE

Review Panel membership

Professor Alistair Hetherington, University of Bristol (chair)

Mr Karl Carter, British Sugar

Professor Gareth Edwards-Jones, Bangor University

Dr Bridget Emmett, Centre for Ecology and Hydrology, Bangor

Professor Les Firbank, North Wyke Research

Dr Matthew Fisher, Imperial College Faculty of Medicine

Professor Sue Hartley, University of Sussex

Professor Steve Long, University of Illinois, USA

Dr Louise Matthews, University of Glasgow

Dr Alan Raybould, Syngenta

Dr Jeremy Wilson, RSPB

Invited speakers at panel meetings

Professor Philip Lowe OBE, University of Newcastle-upon-Tyne
Director, Rural Economy and Land Use programme
(attended panel meeting in December 2007)

Professor Graham Farquhar FRS, Australian National University, Canberra, Australia
(attended panel meeting in May 2008)

Observers

Dr Sue Popple / Professor Sam Evans, Defra
Mr Neil Veitch, Environment Agency
Dr Pamela Kempton / Dr Chris Baker, NERC
Dr Helen Jones, Scottish Government

Secretariat (BBSRC)

Dr Paul Burrows, Mr Brian Harris, Dr Huw Tyson (review secretary)

Terms of Reference for the Review Panel

1. To review current research supported by BBSRC through responsive mode, core strategic grants to institutes and other funding related to environmental change, encompassing relevant research on agriculture and land use, as well as basic research on the responses of plants, animals and microbes (especially pathogens) to changing climate.

2. To analyse research strengths, weaknesses, opportunities and threats, in the context of developing a medium- to longer-term (i.e. 5-10 years) strategy for global environmental change research.

3. To consider how BBSRC's research priorities in this area relate to those of other research councils (in particular to NERC), government departments, devolved administrations and other stakeholders, and to the outlook and needs of industry, all in an international context.

4. To advise BBSRC on priorities for future research in environmental change, in particular on adaptation to and mitigation of the impacts of change, how the high priority areas should be developed and to recommend options that:
    a. promote collaborations as appropriate:
        - within and between BBSRC institutes
        - between BBSRC institutes and the universities
        - between BBSRC and other funders nationally and internationally;
    b. incorporate the most appropriate funding and training arrangements/mechanisms to sustainably support environmental change research in institutes and universities;
    c. optimise the transfer of the outputs of basic research (including that on model systems and species) into application.

5. To report to Strategy Board [amended to report to Council, October 2008].

ANNEX 2

SUMMARY INFORMATION ON OTHER FUNDERS

NERC

The Natural Environment Research Council (NERC) has a mission "to gather and apply knowledge, create understanding and predict the behaviour of the natural environment and its resources, and communicate all aspects of our work". Within an overall remit of environmental sciences, NERC covers atmospheric, earth, biological, terrestrial and aquatic sciences. The main focus of NERC's biological research is on natural (rather than managed) systems.

NERC spends about £40M each year on climate change research[27]. NERC has developed seven themes under which its science strategy (2007-2012) will be delivered:

- Climate system (the Earth's physical climate system but including interactions with biological and chemical systems)
- Biodiversity
- Sustainable use of natural resources
- Earth system science
- Natural hazards
- Environment, pollution and human health
- Technologies

NERC supports research centres including:

- British Antarctic Survey
- British Geological Survey
- Centre for Ecology & Hydrology
- Proudman Oceanographic Laboratory

In addition, NERC supports collaborative centres including:

- Plymouth Marine Laboratory
- Scottish Association for Marine Science
- National Oceanography Centre, Southampton
- Tyndall Centre for Climate Change Research

Defra

The Department for Environment, Food and Rural Affairs (Defra) is the UK government department with responsibilities that include climate change, environmental protection, food and farming, animal health and welfare and sustainable development. Research associated with environmental change supported by Defra[28] includes the following programmes, within the Food and Farming Group and the Natural Environment Group:

- Mitigating pollution and greenhouse gas emissions from agriculture to air
- Climate change impacts and adaptation in agriculture
- Energy in agriculture and food
- Water use (agriculture and the food industries)
- Waste reduction and recycling in the food chain

[27] NERC research: http://www.nerc.ac.uk/research/areas
[28] Defra research: http://www.defra.gov.uk/evidence

- Plant health and bee health
- Animal health and welfare
- Agri-environment policy

In October 2008, the government announced the creation of a new Department of Energy and Climate Change (DECC), bringing together much of the Climate Change Group, previously housed within Defra, with the Energy Group from the Department for Business, Enterprise and Regulatory Reform (BERR).

Scottish Government

The Scottish Government commissions environmental (and other) research[29] to help support and inform government policies for Scotland. Environmental change, and particularly climate change, are clearly recognised as significant drivers for Scotland, and the Scottish Government funds strategic and applied research in the environment, rural, and marine sectors. Total research funding by the Scottish Government is around £70M per annum, of which much will be relevant to environmental change. Programme areas include:

- Responding to climate change
- Protecting biodiversity
- Environmental, social and economic sustainability of rural Scotland
- Profitable and sustainable agriculture (plants, animals)
- Environment – land use and rural stewardship
- Impacts on human health

Much of the research is delivered through seven Main Research Providers in Scotland:

- Macaulay Land Use Research Institute
- Scottish Agricultural College
- Royal Botanic Garden Edinburgh
- Scottish Crop Research Institute
- Moredun Research Institute
- Rowett Research Institute
- Biomathematics & Statistics Scotland

In addition, the Fisheries Research Services (an agency of the Scottish Government) provides scientific support and advice in aquaculture, the aquatic environment, fish health, marine and freshwater fisheries.

Environment Agency

The Environment Agency[30] is the leading public body for protecting and improving the environment in England and Wales, and is a non-departmental public body sponsored by Defra. The Science Department of the Environment Agency is a major supplier of evidence to support the Agency's objectives, and carries out research under seven programmes, with expenditure of £5.3M (2007/08):

- Climate change impacts
- Environment and human health
- Environmental strategy

[29] Scottish Government research: http://www.scotland.gov.uk/topics/research
[30] Environment Agency research: http://www.environment-agency.gov.uk/science/

- Flood risk science
- Integrated catchment science
- Sustainable resource use
- Tools and techniques

European Union

The EU has provided substantial funding for research[31] on environmental change under its Framework Programmes (FP), especially the sub-priority in 'Global Change and Ecosystems' under FP6 (2002–2006). The calls for proposals covered various topics within BBSRC remit, and UK partners were involved in the major proportion of the funded work programmes and Networks of Excellence supported through the four funding calls for this sub-priority.

[31] Database of EU-funded research projects: http://cordis.europa.eu/en/home.html

ANNEX 3

CONSULTATION EXERCISE

As part of the review, a consultation exercise was conducted via the BBSRC website. The consultation document included background information on the scope of the review and a series of questions on priorities for research as well as broader issues related to the review (see below). During its early discussions, the review panel had compiled a set of potential priority topics for research, and the consultation invited comment on these. When replying to the consultation, respondents were asked to bear in mind considerations of BBSRC remit in relation to other research funders.

The consultation was announced via a BBSRC email newsletter (May 2008), which was sent to over 2000 subscribing email addresses. Members of BBSRC research committees and Strategy Panels were notified of the consultation. The secretariat also informed a wide range of potentially interested parties, including the leading BBSRC-funded university departments, relevant research institutes and other stakeholders including scientific societies and non-governmental organisations.

The consultation was open from May to July 2008 and elicited 49 responses, as listed below. Of these, 23 were from universities (17 as consolidated responses on behalf of the university or a department/ school), 6 from research institutes, 6 from scientific societies, 3 from other government research funders, 2 from industry, and 9 from other bodies (including government advisory committees and non-governmental organisations).

The panel and BBSRC are grateful for the numerous thoughtful comments received. The panel considered all responses and took them into account in formulating its final recommendations and research priorities.

Consultation questions

Please address as many questions as you wish. Please keep answers as concise as possible.

Q1. In your view, what are the most important **objectives** for BBSRC-funded research in relation to environmental change over the next 10-20 years?

Q2. What are the key **barriers** to meeting the above objectives, and how might they be overcome? In what topics might there be particular skills shortages?

Q3. What are the main **strengths** and **weaknesses** of BBSRC-funded research in relation to environmental change, and the key current **opportunities** and **threats**?

Q4. Please comment on the **potential priorities** for future research (identified from the panel's initial discussions) [set out in an Annex to the consultation document]. Please suggest alterations or additions to these priorities if you wish.

Q5. To what extent, and by what means, should BBSRC-funded research on environmental change be done in **collaboration with industry**?

Q6. Should BBSRC focus on science addressing primarily UK-related problems of environmental change, or take a more **international** perspective and look to the European or worldwide context?

Q7. How should BBSRC take into account any potential impacts of the research it funds on **developing countries**?

Q8. In considering **agricultural systems**, what should be the balance between research primarily relevant to local, low-input production and large-scale intensive systems? How might the current debate on long-term issues of livestock production be considered? What about long-term food security vs. energy needs?

Q9. What **other specific considerations** should be taken into account – e.g., potential use of **gene technologies** to address problems of environmental change, or the possible impact (positive or negative) of research outcomes on **animal welfare**?

Q10. On what topics should BBSRC research effort be focused to enable the greatest **social, environmental and economic benefits**?

Q11. How should BBSRC encourage consideration of the potential **social impacts** of research relating to environmental change? How should ethical or other social considerations be taken into account in awarding funding?

Q12. BBSRC's current vision is "towards a predictive biology". In the context of climate and other environmental changes, to what extent should BBSRC focus its research capacity on **prediction** of future change?

Q13. Please provide **any further comments** on any issues that are relevant to the review.

The consultation document included the following Annexes**:**

1. Terms of reference
2. Panel membership
3. Potential priorities
4. Glossary of some scientific terms used in the priorities

Responses received

Universities and research institutes
University of Bristol
Cardiff University
Division of Plant Sciences, University of Dundee
Boyd Orr Centre for Population and Ecosystem Health, University of Glasgow
Faculty of Biomedical and Life Sciences, University of Glasgow
Imperial College London
Institute for Animal Health
Institute for Biological, Environmental and Rural Sciences (IBERS), Aberystwyth
Institute of Food Research
John Innes Centre
Lancaster Environment Centre, Lancaster University
Centre for Plant Sciences, University of Leeds
Newcastle University
Centre for Agri-Environmental Research, University of Reading
Rothamsted Research

School of Biological Sciences, University of Liverpool
School of Biosciences, University of Nottingham
Scottish Agricultural College
Scottish Crop Research Institute
National Oceanography Centre, Southampton
University of Stirling
School of Life Sciences, University of Sussex
Research Department of Genetics, Evolution and Environment, University College London

Other organisations
Association of Applied Biologists
BBSRC-NERC Soils Research Advisory Committee
Biodiversity Research Advisory Group (BRAG) and Global Biodiversity Sub Committee (GBSC)
British Ecological Society
British Society of Animal Science
British Society of Soil Science
Defra
Food Standards Agency
Joint Nature Conservation Committee
National Farmers' Union
National Standing Committee on Farm Animal Genetic Resources
Natural Environment Research Council
Plant and Microbial Sciences Committee (BBSRC responsive mode grants committee)
Plantlife International
Royal Society of Chemistry / Institution of Chemical Engineers
Royal Society for the Protection of Birds
Society for Experimental Biology
National Biodiversity Network Trust

Personal responses
Dr Jon Bridle, University of Bristol
Professor Tim Flowers, University of Sussex
Dr Hefin Jones & Professor John Harwood, Cardiff University
Professor Jane Memmott, University of Bristol
Professor Jonathan Silvertown, Open University
Paul Sinnadurai, Brecon Beacons National Park Authority
Peter Sutton, Syngenta
Prof Richard Wall & Dr Eric Morgan, University of Bristol

ANNEX 4

GLOSSARY OF SOME SCIENTIFIC TERMS USED

albedo	the proportion of solar radiation reflected by a surface
ecosystem services	As defined by the Millennium Ecosystem Assessment, ecosystem services are "the benefits people obtain from ecosystems. These include *provisioning* services such as food and water; *regulating* services such as regulation of floods, drought, land degradation, and disease; *supporting* services such as soil formation and nutrient cycling; and *cultural* services such as recreational, spiritual, religious, and other nonmaterial benefits."
phenology	The study of organisms as affected by climate, especially dates of seasonal phenomena such as migration or opening of flowers
systems biology	The study of how function at all levels of biological hierarchy emerges from the interactions between the components of biological systems. Research typically involves quantitative experimentation plus mathematical analysis and reconstruction.
zoonoses	diseases of animals that can also transmit to humans

ABBREVIATIONS

BBSRC	Biotechnology and Biological Sciences Research Council
Defra	Department for Environment, Food and Rural Affairs
EOF	Environment Observation Framework
ERFF	Environmental Research Funders' Forum
GM	genetic modification
LWEC	Living with Environmental Change
NERC	Natural Environment Research Council
RELU	Rural Economy and Land Use (cross-Council programme)
VOC	volatile organic carbon

ANNEX 5

REFERENCES

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