IDENTIFYING KEY SUCCESS FACTORS IN THE QUEST FOR INTERDISCIPLINARY KNOWLEDGE

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January 2011

Project title: QUEST: Capturing lessons for interdisciplinarity
NERC grant reference: NE/H012001/1

Acknowledgements

We gratefully acknowledge the contribution of the following people to this project:

Professor Jacquie Burgess, University of East Anglia
Dr Andrew Donaldson, University of Newcastle
Dr Tom Hargreaves, University of East Anglia
Dr Melissa Lewis, NERC
Professor Philip Lowe, University of Newcastle
Ms Alice O'Hare, University of Sussex
Dr Ismael Rafols, University of Sussex
Professor Joyce Tait, University of Edinburgh
Professor Alan Werritty, University of Dundee
The 64 individuals who participated in the case study interviews
The 20 participants who attended the Interdisciplinary Masterclass

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EXECUTIVE SUMMARY

Interdisciplinarity can be a goal and an endpoint but it is also a *process* that takes place over time. Interdisciplinary funders and leaders ignore this at their peril. Interdisciplinarity rarely happens spontaneously or in a short time frame: it has to be actively sought and managed from the outset. This requires leadership as well as careful consideration of expectations and the examination of some basic epistemological and methodological questions. Interdisciplinary integration has to be catalysed, planned and continuously revisited: it is unrealistic to postpone integration until the end of a project or programme because researchers within the team will have been asking different questions in different ways. This situation may be exacerbated when model-building is the core integrative activity. Successful programmes are mindful of this process and build capacity by allowing for evolution through successive funding phases and by incorporating mechanisms for self-refection and learning.

This report of a 12-month study responds to a directed call from NERC for a project to capture learning around the management and development of large-scale interdisciplinary investments. The research addressed two key objectives:

1. to develop multiple case studies in order to exploit insights from various sources including mechanisms and experiences of UK and international initiatives
2. to promote organisational learning and generate benefits broadly applicable across the long-term future of various UK efforts to tackle complex, multidimensional challenges in this sphere, by drawing transferable lessons of relevance to new programmes, and delivering guidance for funders and leaders of future initiatives in a readily utilisable form

The project took an action-oriented approach and adopted a case study methodology which used a mixed portfolio of data capture techniques (primarily qualitative but supplemented with additional quantitative indicators). The empirical research was structured around four case studies of interdisciplinary environmental initiatives (QUEST, Relu, the Tyndall Centre and UKERC), each representing multi-million pound, multi-discipline and multi-centre investments by the UK Research Councils. These case studies were complemented by a fifth international perspective.

Our analysis of the lessons captured across this set of case studies leads us to identify five key success factors for interdisciplinary programmes which are summarised here with our recommendations for how such success might be achieved:

Locus of interdisciplinarity

In designing an interdisciplinary programme, it is important to identify the locus of interdisciplinarity (e.g. at the level of the individual researcher, project, theme, programme) and to think through the implications of which level(s) are to be the chief platform for interdisciplinarity. This requires an examination of the epistemologies and ontological assumptions involved, focusing on where individuals within the programme draw their knowledge from and how this will impact on the locus of interdisciplinarity. In the case of environmental research, there may be particular tensions between universal and contextualised knowledge, between global and local scale, and between cultural differences where research is conducted on an international level or with non-academic stakeholders.

Catalysis

Interdisciplinarity takes place over time and proceeds through different stages. It is highly unlikely that integration will occur spontaneously at the end of a project or programme unless deliberate steps have been taken to achieve this. Consider how best to tailor the design and implementation of such activities to a particular programme, whether, for example, seed-corn funding for small starter projects, early workshops and/or other activities might help to consolidate collaborations.

Visionary leadership

Researchers need to be motivated, supported and engaged if they are to give of their best in what is, by definition, an unconventional, risk-taking endeavour. Consider the source of interdisciplinary leadership, whether it is provided by funders or by the programme director, or by a team of individuals in charge of component projects, and also how to use external advisory boards to best effect. Leadership is required to inspire diverse individuals on a continuing basis so that their individual motivations align with a common goal while simultaneously managing expectations to match feasible interdisciplinary outcomes.

Active management

It is important to recognise the demands posed by the process of achieving genuine interdisciplinary integration, and to identify responsibilities for various aspects of active management so that this is developed and maintained throughout the life of the grant. Management skills are not routinely taught to academics: while this issue may seem mundane in a monodisciplinary context, this skills deficit is attenuated when faced with the challenges of an interdisciplinary programme. The nature of this active management will vary depending on the locus of interdisciplinarity. Other questions to consider include whether one person or a team will manage the integration, and who (at what level of seniority) plays these roles at which points in the programme's development. Funders' support for active management is critical to achieving the potential value-added of interdisciplinarity.

Learning and continuity

Capacity-building in a variety of forms is critical to the growth and longevity of interdisciplinary research in the UK. This poses challenges for funders and research leaders to ensure that learning from past experiences of interdisciplinary investments becomes embedded within collective organisational memory.

This requires greater continuity – of research networks and communities but also of research careers so that future career options are available for interdisciplinary Early Career Researchers and their expertise is not lost at the end of a programme. This is not to imply that individual interdisciplinary investments should be funded in perpetuity but Research Councils do need to develop more realistic expectations of the time frames within which major change can be achieved: a five-year interdisciplinary programme alone cannot provide the silver bullet to solving complex issues. This requires continuity of funding for multiple interdisciplinary investments – appropriately reviewed – over the long term.

RECOMMENDATIONS

1. At the design stage of a large scale, interdisciplinary investment, consider the ramifications of interdisciplinarity if it is sought at the level of the individual researcher, a component project, a theme and/or at broad programme/ investment level. Pay due attention to contexts created by different institutions, cultures and funders.
2. Research Councils constitute important drivers of interdisciplinarity and may wish to assess how their own structures and procedures reflect good practice,

especially when interdisciplinary programmes require cross-council collaboration.

3. Develop early "warm-up" activities to lay the foundations for mutual understanding, communication, trust and sharing of responsibilities.
4. To ensure development of integration, support opportunities for interaction throughout the course of the grant. This may require additional funding and time for integrative activities and personnel.
5. Research Councils play an important role in shaping investments and on their longer term impacts. This requires an approach that balances focus and flexibility and a realistic understanding of what can be achieved within the timescales of a grant-funded programme. The effective and appropriate evaluation of interdisciplinary investments is a key area where funders could provide better leadership.
6. All directors of interdisciplinary investments should be supported through a peer-mentoring network with a particular focus on translating the vision into the practical reality of tackling the challenges of interdisciplinary initiatives.
7. Active management needs to be emphasised to research teams as vital for success and supported accordingly, for example by sharing organisational learning and providing funding for community-building activities.
8. Some form of formative evaluation should be encouraged for all larger investments to promote self-reflection and the appropriate evolution and development of research. Giving the director discretion to disburse funds in phases during the course of the grant can allow adjustments to be made and facilitate the development of interdisciplinarity.
9. Research Councils should continue to provide strategic funding for interdisciplinary research. This funding should be structured appropriately over time in order both to build interdisciplinary capacity over the course of a particular programme and to ensure continuity of funding for interdisciplinarity across the research community. This requires appropriate evaluation of interdisciplinarity at various junctures.
10. A new vision is required to promote organisational learning for interdisciplinarity within and across the Research Councils. RCUK might consider:

    (i) the establishment of an interdisciplinary reviewers' college (consisting of individuals expert in a range of interdisciplinary areas) to address the common challenge of finding reviewers who are sympathetic to interdisciplinary research and understand how to evaluate it both rigorously and appropriately

    (ii) establishing shared administrative resources for interdisciplinary investments with dedicated administrators experienced in the particular requirements of interdisciplinary research and research training

    (iii) facilitating the development of a cadre of early career and more senior interdisciplinary researchers by hosting community-building events across different interdisciplinary capacity-building schemes and investments. An Interdisciplinary Funders Forum similar to the Environmental Research Funders Forum (now part of LWEC) or the UK Strategic Forum for the Social Sciences could promote shared learning

    (iv) developing an Interdisciplinary Portal analogous to the current RCUK Knowledge Transfer Portal to co-ordinate and consolidate access by the research community to information about funding, training and other forms of support dedicated to interdisciplinarity.

1. INTRODUCTION

There is increasing emphasis, nationally and internationally, on interdisciplinary research to tackle some of the world's most pressing environmental and social problems. In the UK, we have witnessed an increase in funding for strategic interdisciplinary programmes but the lessons arising from such initiatives can be hard to capture and codify. Crucially, where knowledge remains primarily embedded in individuals, it may be unexploited and indeed lost if these players move to different areas of work. Institutional barriers may frustrate exchange of such knowledge and there can be definitional problems in applying the concept of organisational learning to public policy (Common, 2004). While it is evident that the relationship between disciplines is strongly influenced by national funding agencies (Lowe and Phillipson, 2006; 2009), lack of organisational memory may be an issue when staff involved in championing cross-council or cross-disciplinary initiatives move to new areas.

Research Councils have developed effective systems to run research programmes within their core areas but may require additional assistance to capture occasional 'idiosyncratic' experiences – such as running interdisciplinary initiatives. This study seeks to enhance future abilities to tackle pressing, complex problems and draw on national and international comparators to facilitate, in a practical way, not only the generation of integrative scientific understanding, but also the delivery of a wide range of resultant global, social and economic benefits.

Quantifying and Understanding the Earth SysTem (QUEST) is one of the UK Natural Environment Research Council's (NERC's) flagship programmes for earth system science. As this programme approached its close, NERC took the opportunity to commission a study of the experiences of a number of large scale investments in order to advance understanding on the nature of interdisciplinarity in this area of global environmental change research in order to deliver practical benefits to the wider community and provide valuable guidance for future similar initiatives.

We aim to present our findings on effective interdisciplinary working in ways that can be understood by researchers from a broad range of disciplines and not merely those allied with QUEST's earth system science remit. This should maximise the potential for learning, not just across the traditional NERC constituency, but among academics working with other Research Councils. Closely related to these academic beneficiaries are those who control and steer their ability to pursue interdisciplinary endeavours. Our findings on the strategic and institutional aspects of interdisciplinary research will inform university research leaders, such as pro-VCs, who are seeking to position their universities within the emerging opportunities offered by interdisciplinarity. Our findings should demonstrate how best to facilitate such efforts and lessen institutional barriers, again strengthening likely outcomes. The opportunities for organisational learning afforded by this study will aid all Research Council members and staff, in particular those in NERC, in their strategic development of future interdisciplinary initiatives and in their practical approach to programme implementation.

1.1. BACKGROUND AND CONTEXT

By examining experiences of QUEST, in conjunction with other interdisciplinary initiatives, the Rural Economy and Land Use Programme (Relu), the Tyndall Centre for Climate Change Research, and UK Energy Research Centre (UKERC), in the UK and Integrated History and Future of People on Earth (IHOPE), Integrative Graduate Education and Research Traineeship (IGERT) and The Dynamics of Coupled Natural and Human Systems (CNH) Program of the National Science Foundation, this research

draws transferable lessons of relevance to proposed and new interdisciplinary research programmes.

The overall issues tackled by this 12-month study were articulated in NERC's directed call for proposals:

> *"The project should take an action-oriented approach, exploring and evaluating ways to support and expand the UK's diverse and active community of Earth system scientists; foster and enrich the development of useful and usable interdisciplinary Earth system scientists; foster useful and usable interdisciplinary Earth system resources; and provide insights about the kinds of enabling infrastructure that support collaboration, information-sharing and leveraging of resources."*

1.2. OBJECTIVES OF STUDY

The project studied the nature of "deep" interdisciplinarity; examined strategic and institutional aspects of interdisciplinarity (including barriers and enablers); and explored the relationship between interdisciplinarity and policy-oriented research. This project complements previous critical comparative studies (e.g Barry et al., 2008) and our own extensive body of work advising the European Commission and UK Research and Funding Councils (e.g. Bruce et al., 2004; Lyall et al., 2011; Meagher and Lyall, 2005; 2007; 2009) on interdisciplinary community- and capacity-building. The scope of NERC's directed call enabled us to study interdisciplinarity across diverse research areas, including global-scale processes and international perspectives.

The research addressed two key objectives:

1. to develop multiple case studies in order to exploit insights from various sources including mechanisms and experiences of UK and international initiatives
2. to promote organisational learning and generate benefits broadly applicable across the long-term future of various UK efforts to tackle complex, multidimensional challenges in this sphere, by drawing transferable lessons of relevance to new programmes, and delivering guidance for future initiatives in a readily utilisable form

NERC's initial intention had been for a formative study that would assist the QUEST programme in consolidating its interdisciplinary achievements as the programme unfolded. However, the delayed timing of the funding call meant that this aspect became less of a focus of our final study. The emphasis therefore shifted from delivering practical benefits to QUEST to a broader examination of success factors in interdisciplinary programmes. A consequence of this was a slight rebalancing of the contributing case studies, as described in **Section 2**.

2. APPROACH AND METHODS

The project adopted a comparative case study approach using a mixed portfolio of methods in order to triangulate across multiple perspectives and ensure that we captured qualitative insights with additional quantifiable indicators from QUEST[1]. As described below, these included:

- document analysis of both academic and grey literature
- an online survey for QUEST
- learning visits
- semi-structured interviews
- focus groups and a workshop

We took an action-oriented approach, seeking out and capturing often unrecognised reservoirs of tacit learning and good practice regarding the complex behaviours of interdisciplinary research. We captured pragmatic and transferable "lessons learned" as to obstacles and good practice in achieving effective interdisciplinarity in a variety of contexts, at various levels.

The empirical research was structured around four case studies (QUEST, Relu, the Tyndall Centre and UKERC), each representing multi-million pound, multi-discipline and multi-centre investments by the UK Research Councils. These case studies were complemented by a fifth, comprising three comparative overviews with strong international perspectives: IHOPE, IGERT and CNH. The five, full case studies are presented in **Annex 6**. Our initial intention had been to engage with the distributed programmes represented by Relu and Tyndall, as initiatives comparable to QUEST, in contrast with ESRC's more centralised but networked Centre for Social and Economic Research on the Global Environment (CSERGE). After discussions with NERC and in light of the refocusing of our objectives, it was agreed that having four, more equally weighted and similar programmes as cases studies was optimal.

In all the case studies, interviewees (and for QUEST, also survey respondents) were asked to reflect on their experiences and offer advice to those playing various roles in future interdisciplinary initiatives including:

- leaders of interdisciplinary initiatives
- researchers involved in interdisciplinary initiatives
- funders of interdisciplinary initiatives
- support for early career researchers (ECRs)

The intention of this research was to capture, analyse and distil insights in such a way that others facilitating, leading or pursuing interdisciplinarity in the future can benefit. The fact that clusters of similar messages arise across case studies suggests that these may be sufficiently universal as to be relevant to other individuals as well as to research teams or funding bodies in their own internal discussions, planning and ongoing reflection.

[1] As the initial driver for this study, the QUEST case was conducted in more detail, with proportionately more input from interviews, an online survey, a Q sort, network mapping and a bibliometric analysis. This more extensive fieldwork reflects the initial intention of a more formative analysis which, as we noted in Section 1, had to be revised mainly due to timing issues. The fact that we have more data for QUEST does not imply any form of ranking or hierarchy among the case studies.

2.1. FRAMEWORK OF CORE QUESTIONS

The study took the form of a learning review rather than an open-ended, hypothesis-driven research project or a summative programme evaluation of any of the contributing programmes. Accordingly, we sought information about specific experiences across the four comparator initiatives in relation to many of the key dimensions of interdisciplinarity, including:

- effective interdisciplinarity, at various levels of resolution
- interrelationship (if any) between the nature of the research and interdisciplinarity
- affiliations/networks/community-building
- influencing next generation researchers
- challenges of interdisciplinarity
- value-added through management

The key premises with which we framed this work were that:

1. it is possible to capture deep understanding of processes and factors influencing the success of interdisciplinary ventures through participant insights, complemented by other indicators
2. enhanced awareness of such processes and factors can be of benefit to participants, leaders and funders of such interdisciplinary ventures
3. for the most part, processes and factors which influence effectiveness of interdisciplinary ventures do so regardless of subject. It may, however, be instructive to pursue any distinctive influence of a particular type of subject matter (such as the environment)
4. understanding of processes and factors influencing effectiveness of interdisciplinary ventures can illuminate the formation of future collaborations, networks or communities
5. encouraging individuals to reflect and convey messages to funders wishing to encourage interdisciplinarity in the future.

A set of core questions was devised for the study, forming an analytical framework which was constructed in order that information and insights from across the case studies could be integrated for each cross-cutting core question. The detailed analytical framework underpinning this research is provided in **Annex 1**.

2.2. DOCUMENT ANALYSIS

We cite relevant academic literature on interdisciplinarity and grey literature (e.g. on structures and experiences of relevant UK and international programmes) where appropriate in this report. In terms of specific document analysis for this study, while we were already familiar with much of the published literature regarding interdisciplinarity, we sought to expand upon this knowledge by seeking out, in particular, articles relating to environmental research. Through this literature and web searches we sought to identify appropriate international comparator initiatives (and individual contacts to be interviewed). We have also included, where appropriate, in the case studies and elsewhere in our analysis, some secondary analysis of reports such as our own analysis of the Relu interdisciplinary seed-corn scheme (Meagher and Lyall, 2007).

2.3. LEARNING VISITS

To develop deeper understanding, we conducted a series of learning visits. These visits made it possible to conduct many of the semi-structured interviews face-to-face and to learn about the history, structure, location and layout of the different programmes:

- QUEST in Bristol: two visits, the senior team members (PI, Co-I and Consultant) made an initial short visit; later the Research Fellow visited for a week
- Relu in Newcastle: visit by the PI and Research Fellow
- Tyndall Centre in East Anglia: two visits (Co-I, Consultant and Research Fellow)
- UKERC in Oxford: visit by Co-I and Research Fellow

In addition, all four members of the team attended the QUEST/AIMES scientific meeting in Edinburgh in May 2010 to conduct fieldwork, including focus groups and an interactive poster which allowed participants to map their disciplinary affiliations. Two members of the team (Co-I and Research Fellow) attended the QUEST finale event in London in November 2010.

2.4. SEMI-STRUCTURED INTERVIEWS

We conducted a total of 64 semi-structured interviews across the five case studies as detailed in **Annex 2.**

An interview topic guide was constructed following the core question framework (see **Annex 3**). All members of the study team conducted interviews which were either face-to-face or by telephone. Interviews ranged in duration from approximately 45 minutes to just over an hour and were conducted by either one or, where possible, two interviewers to ensure consistency of questioning style while following the core question framework.

The majority of interviews were digitally recorded and transcribed verbatim; where this was not possible detailed notes were taken. The transcripts were imported into NVivo[2] for data management and analysis. Coding was carried out following the analytical framework (see **Annex 1**). The Analytical Framework was then used to collate responses and in the construction of each of the case studies. Relevant (anonymised) quotations from interviews are included in the analysis in **Section 3** to illustrate discussion of the study's findings where appropriate.

2.5. FOCUS GROUPS

We took advantage of the fact that QUEST and AIMES jointly held an open scientific meeting in Edinburgh in May 2010 in order to convene three focus groups during this event. One comprised Masters students from the QUEST programme; and two were conducted with international senior academics who were attending the conference.

We also road-tested the key recommendations towards the end of the project with selected individuals with extensive experience in interdisciplinary research who represented a diverse range of perspectives on environmental and land use research, including natural and social sciences. These senior advisers supported our findings, especially with respect to the key success factors detailed in **Section 4** and offered some helpful enriching. This day-long focus group was held in Edinburgh on 18 January 2011. A copy of the focus group protocol is included in **Annex 4**.

[2] Nvivo is purpose built, commercial software used for classifying, sorting and arranging information produced by qualitative research, www.qsrinternational.com

We had planned to meet with more postgraduates and/or postdocs on the learning visits, to explore their perspective on interdisciplinarity in focus groups. However, none of the institutions visited had either PhD students or postdocs available in sufficient numbers to convene a focus group at the time of the visit, in part because funding was coming to an end. In QUEST and Tyndall, PhD students had largely completed and moved on and many early career researcher contracts had ended. The difficulties in convening groups of PhD students and postdocs also served to underline how dispersed they were in each of the programmes: across UK universities and institutes; and because the nature of their research took them to places as far away as Alaska, Russia, China and Australia.

A number of PhD students and postdocs were interviewed individually in each of the case studies.

2.6. ADDITIONAL QUANTITATIVE METHODS

As the initial driver for this study, the QUEST case was conducted in more detail, employing the additional quantitative methods described in this section.

2.6.1. Survey

We designed and distributed an online survey based on our set of core questions using Survey Monkey[3] (including a mix of Lickert scale, pre-coded and free text response modes). In addition to eliciting information about respondents' experiences of QUEST and interdisciplinarity more generally, we also used it as a means of recruiting additional interviewees, giving respondents the opportunity to meet the research team during the Bristol visit and Edinburgh conference.

We contacted the full QUEST community across all participating disciplines, projects and universities including the Core Team, all PIs and researchers, collaborators and consultants. The survey was emailed on 30 April with two reminders (24 May and 5 June). This yielded a response rate of 78 out of 274 (30%) which is considered high for this type of survey.

The full survey results and analysis are included in the QUEST case study (**Annex 6D**) and relevant results are also highlighted in **Section 3**.

2.6.2. Bibliometric analysis

We know that analysis of past and present collaborations may enable reviewers to outline the likelihood of continuous collaboration beyond the funded period of a project (for example, Boix Mansilla et al., 2006). We therefore commissioned a bibliometric analysis of QUEST publications from Dr Ismael Rafols and Alice O'Hare from SPRU, Science and Technology Policy Research, University of Sussex based on the list of publications by QUEST researchers available from the QUEST website. (The full report of the bibliometric analysis is included in the QUEST case study, **Annex 6D**).

This process identified 196 publications out of 262 provided in the list (75%). The Web of Science records of the 196 papers were uploaded into the text-mining programme VantagePoint. This software was used to make frequency tables, co-occurrence and cosine similarity matrices. Visualisations of networks (maps) were made with network analysis programme Pajek. Additional analyses were carried out using Microsoft Office Excel 2007. Global maps of science and local maps of science were constructed using the methodology presented in Rafols et al. (2010) and Rafols and Meyer (2010).

[3] www.surveymonkey.com

2.6.3. Q sort

We used Q methodology to examine whether, and in what way, it might provide further insights into interdisciplinarity for this study. Q methodology is an approach to examining how people understand the world and involves grouping together people who view the world in the same way (Webler et al., 2009; Giles 2002; Rogers 1995). It requires individuals to sort a set of statements associated with the subject being studied, according to their strength of agreement or disagreement with those statements. For this analysis, we used (with permission) a set of 40 statements that had previously been used for examining interdisciplinarity within the Relu programme (Donaldson et al., 2010) and the Transition Pathways to a Low Carbon Economy programme (Hargreaves and Burgess, 2009).

A total of 12 people completed a Q sort: eight people were recruited at the QUEST/AIMES conference in Edinburgh; a further four completed the Q sort during the learning visit to Bristol. This was adequate for the purposes of the Q sort method but may not have represented the full-range of views held about interdisciplinarity within the QUEST programme.

Sorts were completed by postdocs, research co-ordinators, PhD students and MSc students. Participants were given a set of cards, each card containing one of the 40 statements, and were asked to sort the statements onto a template with a normal distribution (ranging from a score of -5 to +5) depending on the respondents' evaluation of the statement with respect to their own experience of interdisciplinarity. These data were then subject to factor analysis using PQMethod software[4] (Results are reported in **Section 3.2.1** and a more detailed description of the methodology is included in the QUEST case study, **Annex 6D**.)

2.7. CONFERENCE PRESENTATIONS

Two conference presentations have been made so far by members of the project team, primarily to road test the findings from the survey:

- European Association for the Study of Science and Technology (EASST), September 2010, Trento, Italy
- td-net Network for Transdisciplinary Research Conference on Implementation in Inter- and Transdisciplinary Research, Practice and Teaching, University of Geneva, 15-17 September 2010

A further presentation is planned for 7 March when the PI has been invited to speak at a Royal Society workshop on Challenges in Policy Relevant Interdisciplinary Science.

2.8. WORKSHOP

A workshop on Leadership Training for Interdisciplinary Environmental Initiatives was held in Edinburgh, 18-19 January 2011.

The two-day, residential workshop offered practical guidance regarding ways in which PIs and research leaders can make the most of interdisciplinary initiatives. It provided a framework for understanding the often subtle processes that occur within interdisciplinary research. The workshop drew upon the findings of this study, background expertise of the project team and input from/interaction with expert advisors including Professor Joyce Tait (Innogen), Professor Philip Lowe (Relu), and Professor Alan Werritty (Centre for Research on Water). The workshop included a mix of panel discussions, talks and interactive sessions to ensure lively exploration of key issues (a copy of the workshop programme is included in **Annex 8**). The workshop was

[4] www.lrz.de/~schmolck/qmethod/downpqx.htm

open to individuals at PI level and above and attracted 20 participants with a variety of interests and senior roles in different research programmes and networks from fifteen institutions across the UK. Analysis of participant feedback showed that 44% ranked the event 'good' and 56% 'very good'.

2.9. CASE STUDIES

A case study approach was used to provide rounded, detailed illustrations of the four interdisciplinary programmes, focusing on the nature of interdisciplinarity within each programme, how it has developed, obstacles faced and value added. A case study approach allows the subject matter to be examined in depth in a particular place, time and specific circumstance in a way that recognises interactions and complexity (Punch 2009, Thomas 1998). A common case study template (**Annex 5**) was derived from the framework of core questions. In this way, we have recognised the specificity of each of the research programmes but have used the analytical framework to draw out findings that are likely to be applicable to a wider-range of situations.

QUEST, Relu, Tyndall and UKERC form a set of comparative case studies, as all:

- tackle complex environmentally-related problems
- embrace multiple disciplines
- involve researchers at multiple institutions conducting multiple projects, and
- share objectives of contributing, through integration, to pressing issues

To expand upon insights offered by the UK programmes, we also developed a fifth case study which offers a set of three international comparative perspectives.

2.10. INTEGRATIVE ANALYSIS

We have used the analytical framework (**Annex 1**) to develop a rigorous and integrated approach to our data analysis with a focus on distilling lessons learned. The requirements of this study demanded an approach that lay somewhere between applied qualitative research and a summative evaluation. As noted above, our approach might best be described as a 'learning review', drawing on the judgement and expertise of the research team which comprised experienced academic social researchers and professional evaluators.

The objectives of the directed call for this project underpinned our research design and informed the development of the framework of core questions for the study. The first step in qualitative data analysis is one of data reduction and pattern identification (Caudle, 2004). In order to do this, transcripts from the interviews and focus groups were thematically coded using NVivo software. This initial coding, based on the themes identified in the framework, allowed us to interrogate the text, exploring and comparing data across the case studies. This enabled us to identify issues relevant to the analytical questions and to develop both a structure and an analytical narrative. This method allows for a degree of flexibility beyond the confines of a fixed set of evaluation questions and permits the exploration of some broader themes around the concept of interdisciplinarity which may not have been envisaged in the call for proposals.

This methodology uses the voices of the interviewees and direct quotes have been chosen to provide detailed examples of more broadly-made comments to illustrate or emphasise a particular point being made in the narrative which is, itself, grounded in the summation of views on that topic. Identifying information has been removed but every attempt has been made to ensure quotes are viewed in their context. Finally, a form of strategic mapping using Banxia Decision Explorer® allowed us to synthesise our findings and highlight key success factors in interdisciplinary capacity- and community-building.

3. KEY FINDINGS AND ANALYSIS

This section follows the structure of the analytical framework detailed in **Annex 1** and suggests a series of key factors shaping interdisciplinary success. This analysis addresses the following issues:

- expectations of interdisciplinarity
- the interrelationship between the nature of the research and interdisciplinarity
- affiliations, networks and community-building
- influencing next-generation researchers
- addressing challenges of interdisciplinarity
- adding value through management
- possible roles for funders

3.1. EFFECTIVE INTERDISCIPLINARITY AT VARIOUS LEVELS

Expectations of interdisciplinarity play out at different levels across the case studies:

- the many researchers and various combinations of different disciplinary backgrounds
- the range of topics addressed
- the type of questions being asked
- the level at which interdisciplinary is effective

This study found there were different ideas about:

- expectations of what interdisciplinary work is and what it can do
- who or what, interdisciplinary researchers are
- and that interdisciplinarity is effective at various levels

This range of expectations placed on interdisciplinarity runs the risk that a simplistic, 'blanket' approach will actually achieve very little.

3.1.1. Interdisciplinarity at different levels

Across our case studies, environmental, climate and earth system science research utilised interdisciplinarity in different ways at different levels. In QUEST, the core aim was to develop an interdisciplinary model informed by three thematic strands of work. Interdisciplinarity within Relu was perhaps more project specific but these were embedded within the overall programme. Tyndall had a focus on programme-level interdisciplinarity with an emphasis on capacity building and UKERC's strong strand of policy relevance was a key driver for interdisciplinarity.

The case studies therefore show interdisciplinary work occurring at:

- programme level
- theme level (i.e. a sub-programme level, integrating topic(s) across projects)
- project level, within a project team or individual project members
- training/teaching for PhDs and masters[5]

Programmes have used different methods of integration, including modelling (see **Section 3.2**). What is clear is that interdisciplinary integration can occur at different levels and an improved awareness of the main locus of interdisciplinarity can inform the management of the programme and its component projects.

[5] Issues related to researcher development are addressed in **Section 3.4**.

The level at which interdisciplinarity is effective is influenced by the setting up, focus and agenda of an interdisciplinary investment. It is also influenced by the underlying institutional contexts, the type of interdisciplinarity that is being sought (see **Section 3.2.3**) and an awareness of its conceptual foundations (Khagram et al., 2010). As these authors describe in more detail, an understanding of the relationships between the theories (e.g. explanatory, understanding, predictive), philosophies (experimental, comparative, etc) and research strategies (positivist, interpretivist, constructivist) deployed across a research programme can provide a helpful framework for integration. In our study, the aims, objectives and knowledge bases of each of the case studies were different, although often sounding similar in their rhetoric and representation, especially with regard to taking an interdisciplinary approach to addressing an issue, answering a question or solving a problem.

Programme Level

All of the initiatives studied were intended to be interdisciplinary at the programme level but the extent to which this was achieved varied. One might ask whether a programme's structure reflects (and fosters) the type of interdisciplinarity that the programme is trying to achieve. Contrast, for example, Relu, where each project was required to be backed by an interdisciplinary team of social and natural scientists, with the structure of QUEST where the 'social' projects were collected together in one of the themes and several projects in other themes were explicitly not interdisciplinary.

UKERC emphasised enabling interdisciplinarity rather than forcing it and a recognition that much interdisciplinary research develops organically. Interviewees suggested that UKERC appears to have been effective in taking on an area of research with individual, scattered researchers and bringing them together into an effective programme.

Integration of the social sciences was always a key element of the QUEST core team agenda and they facilitated outward-facing activities (for example, the development of the IHOPE initiative) and established working groups with the aim of synthesising data, writing interdisciplinary papers and developing future collaborations. But this integrative activity was not reflected across the programme, and indeed many of the interviewees had little interest in engaging with the social sciences and did not feel that it was relevant to their research. This is reinforced by findings from our survey and bibliometric analysis which indicate only limited interaction between themes.

Theme Level

There were two ways in which interdisciplinarity occurred at theme level. First, through themes that were designed and funded to be interdisciplinary and, secondly, at the PI level where a PI on a project in one theme might be a Co-I on a project in another. This second mechanism is dependent on PIs being able to commit sufficient time to co-ordination across projects but some interviewees felt that PIs had not had enough time for these demands of interdisciplinary work.

The Relu Strategic Advisory Committee initially identified four interdisciplinary themes as the core areas of research for the programme but these had the flexibility to evolve in response to subsequent phases of funding. Within Tyndall, heads of themes acted as brokers encouraging the development of new disciplinary combinations. From our interviews with QUEST participants, interdisciplinarity in Themes 1 and 2 appeared to have been situated within the projects; in Theme 3 there was a shift towards interdisciplinarity within some of the projects, which was mostly attributed to the introduction of social science and 'human' element to the models.

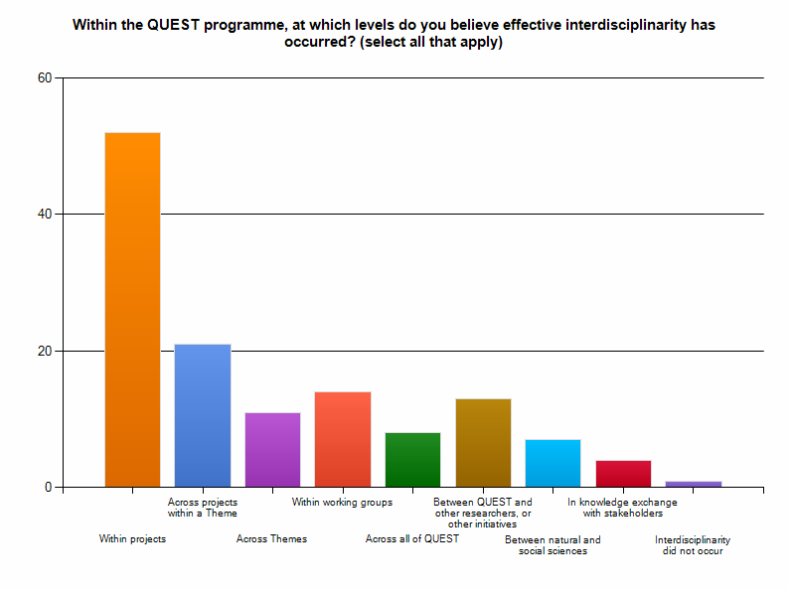
Project Level

Many of the programmes studied had stated a requirement that constituent projects would be interdisciplinary. Success was seen to vary across the case studies, within

each there were projects that were regarded as examples of highly successful interdisciplinary work, and inevitably a few which could have worked better. A small number of interviewees took a cynical view, saying that people had only added an interdisciplinary dimension to their project (usually in the shape of some social science) to obtain funding and then did not pursue it. Indeed, the QUEST survey shows that interdisciplinarity occurred predominantly within projects, to a much lesser extent across themes, and only 12% of respondents believed that effective interdisciplinarity had occurred across the programme as a whole (**Figure 1**).

All Relu projects were required to integrate novel contributions from across the three research council communities. Each project had to have a social science contribution, so projects could combine biological science and social science, environmental science and social science or biological, environmental and social sciences. The social-bioscience axis within the programme was initially weaker but strengthened by the third wave of funding (Animal and Plant Disease). This mandated within-project interdisciplinarity reinforced frequently articulated programme-wide goals of interdisciplinary integration and, at each funding round, proposals that had insignificant or token aspects of natural science, or token aspects of, or no aspects of social science, were formally excluded from consideration.

Figure 1: Locus of interdisciplinarity within QUEST programme



3.1.2. Interdisciplinary and policy relevant outputs

The need to deliver policy-relevant research was identified as a driver for interdisciplinarity.

Tyndall publications have led to policy change, including influencing the Stern review, engaging with the Science and Technology Committee at the House of Commons and informing the establishment of UKERC. Tyndall has also contributed to theory development, including Adaptation Theory, and has "pulled up the standards" of interdisciplinary working, and produced a cohort of interdisciplinary researchers that has spread into academia successfully (see **Section 3.4**).

Some informants from QUEST felt that interdisciplinarity was a means to an end, allowing them to link ideas about research and policy together and the International Advisory Board (IAB) pushed QUEST to look hard at how it engaged the policy community. Three of the Theme 3 projects were at the policy/natural science interface.

From across the case studies, several interviewees indicated their interest in delivering something relevant to policy beyond writing academic papers. It was argued that there was a political urgency to environmental issues and we were often told that getting people to behave differently has become a real research priority:

> *"When it comes to the policy response stuff or trying to do good science to inform policy then, I think, then that's where the interdisciplinarity almost, has to come in really. So I don't think there's anything necessarily special about doing climate change research that's special to interdisciplinarity, but I think, to do climate change research with policy, you kind of have to be interdisciplinary in order for it to work really*."

The value of engaging with stakeholders was highlighted: for example, an interviewee insisted:

> *"[F]lag up this issue of how important stakeholder engagement in advance is…in interdisciplinary research….it's not just the academic expertise, it's that people out there doing it, trying to implement it, wrestle with the policies, understand the information, make it workable, I think, they are the other expertise in interdisciplinarity… they're just a different type of expert".*

We return to this issue of policy relevance in **Section 3.2.1** when we discuss some of the motivations for interdisciplinarity.

3.1.3. Expectations of interdisciplinarity

Much of the rhetoric that surrounds the rationale for interdisciplinarity includes: solving a real problem for society; for research to be policy relevant; and to engage with stakeholders and/or users. A key thing that we learned from the interviews was that researchers' (and funders'/policy makers') relationships with interdisciplinarity were based on a range of assumptions and expectations of what interdisciplinarity can achieve. These included:

- providing new insights
- creating global collaboration (both geographic and intellectual)
- integrating (ideas/methods/data/models)
- policy relevance
- user relevance
- providing solutions to problems
- providing predictions

All of which were seen as positive contributions to knowledge and to society.

It followed that interdisciplinary researchers were expected to deliver on these assumptions and expectations by:

- thinking 'in a new joined up/integrated way'
- using multiple methods or developing new methods
- integrating existing data and/or models to produce new results

Many researchers also laboured under the expectation that they would become interdisciplinary simply by participating in any or all of these activities. Some of those without any previous experience felt they had not comprehended, and were therefore not prepared for, the demands and complexity of interdisciplinary working; others felt that they had a fair idea of what they were getting involved with, but were keen to learn more, develop skills and new expertise.

How interdisciplinary is a researcher in their own right, and how interdisciplinary is a researcher by dint of participating in an interdisciplinary project or programme? Across the case studies we found small numbers of people who had taken a natural science degree and then a masters in a social science subject (e.g. policy studies), a small

number had taken a degree in a natural science subject and then a masters or PhD in an earth system/climate composite field (e.g. atmospheric science). However, the majority of interviewees had gained their interdisciplinary experience by working on a project and learning as the project demanded. The people who had learned or were learning to be interdisciplinary whilst on the job were doing it to different degrees:

- some said it was about learning to communicate with researchers from other disciplines
- some said it was more than communication – you need to understand how other disciplines operate (e.g. in terms of data collection)
- very few said they needed to understand the theoretical approach that other researchers work with – (some said it was not that they weren't interested - although many weren't - but because it was a huge time commitment and could not be done on top of an already busy schedule)
- in QUEST it seems the greatest demands for understanding other researchers' methods (and occasionally theory) were made of the modellers
- there was also a pragmatic attitude where researchers said they learned as much as they needed to learn to get the job done

Overall, interviewees across all the case studies were striving to meet these expectations. A few of the interviewees said that they just did what they usually do and that although they knew their project was supposed to be interdisciplinary they had no involvement in that process. A small number of interviewees said that they did not want to do interdisciplinary work in the future, as it just did not suit them. Mostly interviewees thought that future research in their field would continue to be interdisciplinary and that they were better equipped by their experience; many were very enthusiastic about interdisciplinary approaches.

The expectations/assumptions could all be seen as occurring at different stages of interdisciplinary research, in funding calls, programme proposals, and project proposals. The problem was sometimes that what was envisaged and what was feasible or delivered were not the same thing. One of the issues with this was the different scales on which the research was being conducted, i.e. ecological niche, regional and global, which gave rise to different scales of data collection, and issues of data integration (discussed further in **Section 3.2**).

A further issue that has been addressed by others (e.g. Barry et al., 2008; Oberg, 2010) but is perhaps not given sufficient prominence when interdisciplinary programmes are being established, is the question of the *type* of interdisciplinarity that is being sought and the impact that this will have on the management and design of the programme. We have characterised this as the contrast between 'academically-oriented' and 'problem-focused' interdisciplinarity (Lyall et al., 2011). To stereotype, this might be summarised as the contrast between deep interdisciplinarity, which strives to develop new ways of thinking, and pragmatic interdisciplinarity that has a job to do that requires collaboration with others including, most probably, research users and other stakeholders.

Deep interdisciplinarity, which requires extensive experience and time to reflect, was the least frequently found or discussed in the interviews. The majority of interviewees were operating at the pragmatic level with varying combinations of ways of working and degrees of integration between researchers/data/models from different disciplines, and/or varying degrees of engagement with others who were generally not academics.

3.1.4. Interdisciplinarity and identity

Interdisciplinarity can be fostered between disciplines in the natural sciences and between the natural sciences and technology or it may increasingly refer to the

combination of natural and social sciences. Interdisciplinary research can therefore take place in many different forms and for different purposes and this will have a bearing on the nature and conduct of that research. Knowing what we mean by interdisciplinarity in a particular context gives clarity to communication and purpose within interdisciplinary endeavours.

Within Relu, many of the disciplines, such as ecology or geography, are themselves 'portmanteau disciplines' which are broad, outward-looking and open to other methods (Phillipson et al., 2009). Social scientists within Relu have illuminated social preferences, attitudes and values and facilitated participatory approaches, and they have also offered different perspectives to help reframe scientific problems, improving understanding of how socio-ecological systems function and providing alternative forms of interpretation and judgement (ibid.). Relu spans a broad range of methodologies across a wide variety of disciplines. The interdisciplinary approach adopted by Relu brings the knowledge of different disciplines into a positive dialogue, trying to move away from simplistic assumptions about 'technology push' or 'society pull'.

UKERC had a strong component of interdisciplinary researchers (almost all interviewees identified themselves as interdisciplinary although this may not be true across all themes) and often with experience outside academe. One interviewee indicated that one of the reasons interdisciplinarity works in UKERC was because, by and large, it includes the right group of people who are willing to collaborate across disciplines in the first place. He, himself, felt that this had been an opportunity for him to be more proactive about interdisciplinarity. UKERC was seen to facilitate interdisciplinarity because it has provided a framework that encouraged rather than discouraged it. It posed problems that actually needed a range of inputs and involved researchers who understood and appreciated the need for different inputs. Interviewees stressed that the topics and approaches were interesting, and they particularly valued the degree of flexibility allowed in the research process, yet having a sense of direction and being part of a larger, coherent whole.

Tyndall conducted an exercise with their researchers over three years, up to the publication of *Truly Useful* (2006), where researchers plotted where they felt they were located on an interdisciplinary triangle (referred to later as the 'Tyndall triangle'). Not everybody migrated over the course of the exercise, but those that did tended to move towards a social science cluster. A lot of people came as environmental scientists, but then became more interested in policy, causing them to migrate in the direction of social science. Conversely, the social scientists did not migrate and were the least integrated of the disciplines, only one social scientist moved in the direction of environmental science.

The global nature of the QUEST programme, with its aim to develop an integrated model of earth system across many science themes meant that a wide range of disciplines were involved, including chemistry, physics, engineering, economics, archaeology, climatology, hydrology, statistics, geography, geology, social science, policy studies, ecology, and oceanography, as well as integrated subject areas such as biogeochemistry, paleo-climatology, atmospheric science, ecosystems, forest science, ocean science and paleo-oceanography. There was particular emphasis on the integration of biology, chemistry and physics because they were the 'hard' natural sciences that underpinned the model. In some, if not all of the QUEST projects, distinctions were made on the aspect of a system that a researcher worked on, rather than by 'discipline'. Different scientific interests also drew distinctions between modelling and observational science.

However, talking about disciplines was difficult for some interviewees. They felt that so much depended on definition:

"chemistry versus climate and physical sciences - are they different disciplines or is it the same discipline? And oceanic versus atmosphere modelling - is it a different discipline or the same discipline? …… within any of these single disciplines you can define another 2, 3, 5, 10 smaller disciplines all connected.... What we call disciplines now is totally different from what was called discipline 50 years ago"

A few of the interviewees thought that disciplines or interdisciplinarity were unhelpful notions and irrelevant when "you just need to get the job done".

The distinctions made by QUEST interviewees about whether they thought of themselves as interdisciplinary varied. Some viewed working with anyone from another discipline as interdisciplinary; some of the interviewees who classed themselves as belonging to 'integrated' disciplines or departments such as 'biogeochemistry' or 'earth sciences' considered themselves interdisciplinary; others felt it was more about working across different fields of interest, for example, someone working on atmospheric science would feel they were doing interdisciplinary work if they were working with someone from hydrology; and some natural scientists felt it was only interdisciplinary if you had to work with social scientists, although distinctions *between* the social sciences were rarely made. (The main exception to this social science generic identification was economics. Some interviewees who had worked in projects with economists found it very helpful, while others said it had created problems because they found economic models inflexible and therefore difficult to accommodate in their own work.)

Modellers had mixed views on whether they saw themselves as interdisciplinary: some thought they were interdisciplinary because they worked in integrated fields, for example, geochemistry or paleo-oceanography, whereas others felt that they fitted in one discipline and talked to others across a gap. Their identity was related to a discipline, or particular field of research, and modelling was something they 'did'.

The bibliometric analysis shows that QUEST papers cite references and were published across a diverse set of disciplines in the broad disciplines of ecology, geosciences and environmental science and technology (S&T). The bibliometric analysis conducted for our study finds interaction with neighbouring disciplines, but not with disparate disciplines. Rafols and O'Hare suggest (**Annex 6D**) that QUEST is therefore a particular type of interdisciplinarity: the type practised by 'interdisciplines' already or quasi-established, rather than creating new and unexpected disciplinary combinations.

3.2. INTERRELATIONSHIP BETWEEN THE NATURE OF THE RESEARCH AND INTERDISCIPLINARITY

3.2.1. Motivation for interdisciplinarity

Across the case studies interdisciplinarity was identified as being the obvious way to progress the research agenda. The following reasons were given for this.

The interdisciplinary nature of the subject under study

The research subject areas covered by the case studies such as earth system, climate change, energy research and sustainability were widely perceived to be inherently interdisciplinary areas of research. Nevertheless, it was also recognised that effective research could be undertaken in specific aspects of each. Monodisciplinary research can be effective in researching specific 'pieces' of the issue but cannot integrate these pieces into a whole. The global scale of the QUEST project, studying complex global problems was recognised as also requiring an interdisciplinary approach.

The problem focused nature of the research

Many of the researchers interviewed identified themselves as being problem focused. Interdisciplinarity therefore tended to be seen as a means to an end rather than something of merit for its own sake. Researchers were motivated to identify the relevant disciplines to help understand or resolve an issue rather than, say, viewing this as a way of furthering development within an individual discipline.

The focus on providing policy relevant research

A strong driver for interdisciplinary research was the desire to provide policy-relevant research. The motivation for this was not just the push from Research Councils: some researchers held personal environmental commitments leading to a sense of urgency about responding to the issues raised by the research. Researchers referred to wanting more than just academic publications as outputs from their research.

There was mixed evidence from the case studies of engagement with what the pathway to policy impact would be. Several different approaches could be identified:

- as noted earlier, interdisciplinarity could be used almost as a synonym for policy relevance with an apparent expectation that policy relevance would automatically flow from being interdisciplinary (which of course is not the case)
- there were relatively undeveloped expectations of how interdisciplinarity would enable policy relevance, for example, expecting social scientists to help communicate climate change issues to the public
- engagement with the policy process was facilitated in UKERC by a specific strand focused on synthesising results for policy relevance and engaging with policy and stakeholder communities both in determining the areas of research to be synthesised and establishing a programme of presentation of the results to policy communities
- in Relu, engagement with the policy process was facilitated by an extensive programme of exchanges and work-shadowing that enabled mutual understanding of the issues and evidence at stake
- in Tyndall, relevant stakeholders were involved at the outset of some projects: helping shape the research, helping with data, advice on how to deal with problems and identifying key aspects worth researching. Thus a much greater degree of engagement was established

An aspect that was briefly mentioned was the involvement of policy makers in model development, for example, creating a portfolio of policy options that might be regarded as politically feasible. A further question was raised as to whether policy makers needed better models, as the question ‘what would constitute a better model’ remained unanswered.

The multifaceted nature of many of the disciplines in the research consortia

Research disciplines such as ecology, geography, agriculture or development are already composites of several different disciplinary origins (the so-called ‘portmanteau’ disciplines or ‘interdisciplines’). This affects the way in which these composite disciplines conceive of research problems; for example, it was suggested that most environmental scientists will conceive of problems from a systems perspective (whether explicitly or implicitly) because their focus is on understanding many connected factors. Furthermore, any research on sustainability will inevitably involve a human component which immediately raises questions of alternative conceptions and values. It was argued that an understanding of both natural and social sciences is therefore needed.

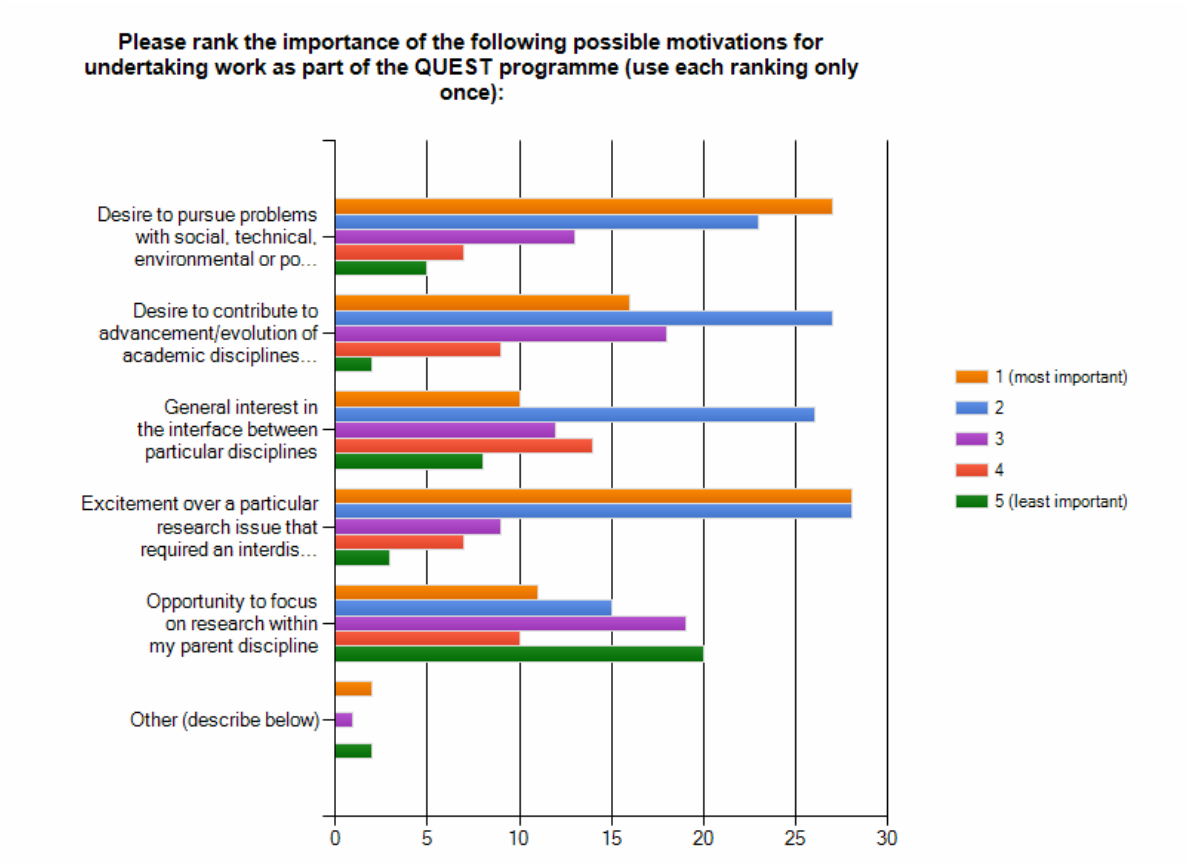
The lack of definition in some of the research domains

The lack of clear boundaries in some research areas, for example climate change adaptation, means that no one, single discipline has developed to address it. Consequently, different disciplines are able to bring their expertise to bear on the subject where the boundaries have not yet been defined. It was suggested, for example, that terms such as 'vulnerability' and 'adaptation' are still under discussion and questions around how to articulate the values that are at stake have yet to be resolved.

A more detailed look at motivations within one case study

We were able to examine motivations in more detail in the QUEST survey (**Figure 2**), 'Excitement over a particular research issue that requires an interdisciplinary approach' and 'Desire to pursue problems with social, technical, environmental or policy relevance in the "real world" ' were ranked as most important, with 'Desire to contribute to advancement /evolution of academic disciplines or new (sub)disciplines' and 'General interest in the interface between particular disciplines' next in importance.

Figure 2: Motivations for taking part in QUEST programme[6]



We used the Q sort method to examine, in more detail, understandings of interdisciplinarity within QUEST. The Q sort method identified two factors (two groups) with different understandings of their own experience of, and motivations for, interdisciplinarity.

[6] Y axis labels in full: Desire to pursue problems with social, technical, environmental or policy relevance in the "real world"; Desire to contribute to advancement/evolution of academic disciplines or new (sub) disciplines; General interest in the interface between particular disciplines; Excitement over a particular research issue that required an interdisciplinary approach; Opportunity to focus on research within my parent discipline; Other.

One group (factor), which we termed 'Problem solvers', was focused on the role of interdisciplinarity in solving problems. A second group (factor), which we termed 'Individual careers,' was focused on the role of interdisciplinarity in the context of their own careers. (Further information on the Q methodology analysis and the full list of statement rankings are given in **Annex 6D**.)

Based on the ranking of the statements, we have developed the following characterisation of the views for the two factors which illustrate different motivations for interdisciplinarity:

> Factor A: Problem solvers
>
> The point of view captured by this factor emphasises the importance of interdisciplinarity as a technique for solving problems. This factor indicates that problems to be solved are more important than disciplines, particularly since the real world is not divided up by academic discipline. Therefore, interdisciplinary approaches are a way of addressing these real world problems which will also provide research that better serves the needs of the economy and promotes application of research in policy and practice. Interdisciplinary research is underpinned by synthesising and integrating research output and by working together to find things out. Interdisciplinary research allows other disciplines to challenge any ingrained assumptions within one discipline.
>
> Factor B: Individual careers
>
> The point of view captured by this factor emphasises the importance of interdisciplinarity as contributing to improve the researchers' own research. This factor agrees with the 'Problem solvers' that the real world is not divided up by academic disciplines. However, the focus of working with researchers from other disciplines is the context of broadening horizons and improving the individual's own research. Different disciplines offer more than just different perspectives as they can also challenge ingrained assumptions. Underpinning this is an understanding that interdisciplinarity is about working together to find things out. Finding a common language is a problem to interdisciplinary working. However, some disciplines are better equipped than others for interdisciplinary collaboration.

3.2.2. Modelling, integration and interdisciplinarity

Models have been an important method of interdisciplinary integration in each of the case studies, ranging from linking models across the earth system, modelling energy systems to using economic/ecological modelling in specific situations[7]. Models were identified as providing a focus for the research that could aid integration but could also become a source of friction.

Models were variously conceptualised as a way of encapsulating information from other disciplines or translating an abstract of the universe into a programming language. Individual disciplinary specialists, for example, water engineers could work on a specific project which could then be incorporated into over-arching models integrating with monodisciplinary modules from other disciplines. Visualisation and mapping from models was also identified as a way of integrating data from models.

An example of integration as a motivation for modelling efforts was given from the QUEST project where, as one of the cross cutting and integrative activities, modellers

[7] Other approaches were also used to synthesise input from a range of perspectives such as scenario development An example of this was the 'Energy 2050' report (available at www.ukerc.ac.uk/support/tiki-index.php?page=UKERC2050homepage accessed 26/1/11) from UKERC which used existing models but used scenarios from other researchers and thus provided a wider-range of perspectives and assumptions.

conceptualised a framework for, and were building, the new fully-coupled QUEST Earth System Model, to bring together atmospheric, terrestrial and marine models. The emphasis on modelling as a route to interdisciplinarity in QUEST was highlighted by the Q sort results (see **Section 3.2.1**). Respondents from QUEST identified interdisciplinarity as being about synthesis and integration. Comparators from the Transition Pathways to a Low Carbon Economy programme (Hargreaves and Burgess, 2009) gave much lower weightings to this aspect of interdisciplinarity, although responses were otherwise very similar. A plausible explanation is that the Transition Pathways project consisted primarily of engineers, in contrast to QUEST with a preponderance of modellers (Burgess, personal communication).

Modelling could be conceived of as a way of integrating input from disciplines into a single result. However, in contrast to a simplistic "additive" approach across disciplinary inputs, modelling for complex issues may involve multiple options and decision points. This often demands an iterative process requiring the integration of qualitative and quantitative data which may call for discussion, judgement and conceptualisation. A number of practical challenges to achieving this were identified.

3.2.3. Data collection and modelling

In some of the cases, the main challenges were perceived to be less between disciplines than between computer modellers and data collectors. In terms of interdisciplinarity, some of the modellers said they had more difficulty understanding what the data collectors were doing than they did in understanding what a modeller from a different discipline was doing.

Many of the issues related data quality and standardised. Modellers expressed frustration about the lack of suitable data and their inability to control what data were being collected. Data collectors expressed concern at the apparent failure of modellers to fully appreciate the complexity of data as modellers sought to simplify data to enable modelling. Views on incorporating data from literature into models reflected the same tension, with data collectors concerned at the confidence with which modellers would incorporate such data when the data collectors were aware of problems with it. Part of these tensions also reflected the scale of the models. Restricting models to small areas would enable more detailed modelling. In global models, the data are much more patchy. The issue of scale (see **Section 3.2.4**) is often an important factor in environmental interdisciplinarity.

In one of the international case studies, ownership of models became an issue with data collectors feeling that modellers were excessively proprietary about their models which in turn discouraged interdisciplinary engagement.

Integrating models

Integrating different models raised a number of issues. Sharp differences in data mean models may not be sufficiently compatible to be pulled together:

> *"one group will have parameterised their model in one way and implemented this numerical scheme for doing it, and another group will have done something subtly different, and when you want to match the two,…It's very hard to get a model that runs with both terms"*

As a result, integrating models took considerably longer than expected (in the view of one researcher not 2-3 times longer than anticipated but 10-15 times longer). There were calls for realistic expectations of the amount of work required to integrate models. It was also suggested that many research projects were not fully able to realise the potential of the integrated models as most of the project time was taken up with developing the model and it was only during the integration phase that many important bridging interdisciplinary research questions were identified. A second phase of funding

was suggested, to allow models to be run to address some of the new research questions.

Timing issues

Timing of research to enable integration of interdisciplinary research within a model was also identified as important to resolve. Although, theoretically, models could be used to integrate data, as noted above, in practice they tend to be completed at the end of a research project when it is too late to benefit from the integration. A further aspect on timing is that any data collection (such as social science scoping studies) will take time and delay the start of model-building activities.

Incorporation of social science in models

Incorporation of social science data in models presented considerable conceptual and methodological challenges. For example, social science data in particular may not be readily available in the format required by modellers. As with any other data, some challenges were related to the nature of data or to data quality, although the issues were more complex. Some social data are very hard to obtain: for example, individual household energy use data may be proprietary, temperature levels in different types of room across a range of housing stock may not be available. Measures of attitude may not be reflected in actual behaviour and modelling may need to address this in different ways. One attempt at providing a taxonomy of ways in which behavioural data can be incorporated in modelling is found in Cooke et al. (2009) looking at quantitative methods of assessing welfare and understanding and predicting behaviour.

While modellers may express frustration that they are not being provided with appropriate data for models, social scientists expressed frustration that they were expected to have data readily available 'on a silver tray'. An illustration would be the challenge inherent in converting context and meaningful narrative derived from, for example, archaeological data such as shards of pottery, into a form that could be seen as useful by modellers.

Other social science data may be more difficult to quantify and it may not be possible for some questions to be answered readily by models, for example, why are some humans affected by an environmental change more than others? There was a view that, while modelling is a very important step in understanding systems as a whole, it will never be able to completely include the human dimension. Therefore models may need to be supported by additional social science analysis.

Working with stakeholders

A number of models worked with stakeholders to improve their interdisciplinarity and incorporate practical knowledge. One example was a modelling project within Relu where knowledge from land managers was incorporated into models based on ecological and spatial data of deer distribution resulting in an increase in the predictive ability of the model (Irvine et al. 2009).

Another approach adopted within UKERC was to use stakeholder workshops to develop scenarios. These scenarios were then translated into models by the modellers, because the stakeholders were perceived not to necessarily understand the implications of what they were saying in terms of impact on the economy or what might happen to greenhouse gas emissions. The modellers saw it as their job to translate the scenarios into models and then to present the results to stakeholders and allow them to verify the model.

Limits to models

A number of limitations were identified to the use of models in interdisciplinary research. Many researchers highlighted the need to recognise that a model is not the

real world and even complex models require huge oversimplifications. As a result, concern was expressed that the models themselves become the focus of investigation, with the real world downplayed. In particular, there was a concern that unrealistic expectations of modelling could be made by policymakers and greater realism was called for in expectations as to what models could achieve.

Within the constraints of this study, our analysis of the role of modelling may not be sufficiently comprehensive to address all of the subtleties of this complex issue. What is clear, however, is that, where models are a key vehicle of integration within an interdisciplinary programme, particular attention needs to be paid to their limitations and challenges.

3.2.4. Scale and interdisciplinarity

Earth system and interdisciplinary environmental research more widely has to deal with a range of issues related to the scale at which research is conducted. Key dimensions are spatial and time related. Research can focus on a small geographical region in great detail or it can involve modelling earth system as a whole and all stages in between. The time scales covered can range from decades and centuries to geological time frames. This vast range of scales presents particular challenges to environmental research and, more particularly, to the interdisciplinary aspects of such research. Providing analytical and predictive integration of relevant human and natural system processes involves developing novel, integrated approaches to these complex interactions.

Scientists may tend to focus on researching small areas in great detail but decision makers require tools that can provide information on regions, countries and global scale. In terms of geographical area, data can be collected on a micro, country or global level. Much of the study of terrestrial ecosystems tends to be on the scale of kilometres covering, say, a specific water catchment area. Scaling up this knowledge to a global scale presents challenges. Lack of data at a global level causes problems. Some regions of the world have relatively good sources of data but other areas of the globe are very lacking in data. Typically, some groups were identified as working on high definition in-depth data from a geographically 'local' area which is insufficient in range and contains too many specifics to translate into data for a 'global' model or analysis.

Issues of scale may arise around automation and ability to run different models different numbers of times: an example was given of a project where the intention and presumption by some members of the team was to automate and run a model 1,000 times, but the nature of the model was that it could only be run 2-3 times within the project period.

There is also recognition that humans have been interacting with their environment throughout their evolution and may potentially provide lessons on current and future interactions. However, this aspect has not traditionally been a subject of study. Questions remain as to what sorts of conclusions can be drawn from historical and archaeological data. What are the relationships between findings and development of human society, and the relationship between what humans do and how nature is affected? And if nature changes regardless of people, how does this affect humans? Spatial and time related aspects may interact as archaeologists, for example, work to understand changes over time at the level of a single site, not even a region. How can such data be used to inform a wider-understanding of human-environment research? Social science data generally tend to be very localised and specific and it is difficult to derive globally relevant information from this. One respondent, for example, argued that understanding of adaptive capacity and processes of adaptation is very good at the village and household level, but is very difficult at the regional or country level. The

merging of past data with expectations of the future may influence the mix of disciplines, so that some human sciences may be less appropriate to include in studies of geological timescales.

The complexity of trying to combine data from different sources should not be underestimated. It is easy for researchers in one discipline to make assumptions and oversimplifications of what can be provided from another discipline. Alternative approaches to modelling may be needed where data are not available, appropriate or sufficient to integrate. For example, initiatives to develop conceptual templates for integrative work in human-environment research have been piloted (Newell et al., 2005). More feasible and more readily researchable approaches, such as the use of case studies in IHOPE (see **Annex 6E**), may be more effective and worth considering.

Appreciation of the importance of different scales can therefore be an important product of interdisciplinary working. When asked about challenging chasms spanned by QUEST, one person brought up this greater appreciation of timescales as a key accomplishment:

> *"I think one of the biggest points actually was the time dimension, most people who studied change in the past, the paleo community, the modelling community and the processes community, I think if anything that would be the centrepiece of QUEST's success. The people there have an exceptionally good feel for the importance of understanding how the earth was operating in the past, and I think they built that excitement for and interest in, people (who came) into QUEST at the beginning without much knowledge of why we even worry about the past at various time scales. And so I think, to me that was some of the most exciting stuff they did and I think globally it's one of the most important."*

3.3. AFFILIATIONS, NETWORKS AND COMMUNITY-BUILDING

3.3.1. Networking and community building

The case studies have used a number of mechanisms to foster networking and community building. For example, the UKERC annual assembly was praised for being well organised and having a good mix between presentations and time to discuss, talk and explore new ideas, as well as establishing links through informal interactions. Prior to the founding of UKERC, the energy research community was described as scattered, largely technically led with pockets of policy research. Partly through UKERC, the energy research programme has been widened, the disciplinary base has increased and there is also now an active community of social scientists in the area. As a result, people's networks have changed but since most interviewees were already established interdisciplinary researchers, the networks tended to relate to new countries and new policy domains.

There is also evidence that Relu, through its pro-active community-building mechanisms, has helped to catalyse a cultural change in interdisciplinary outlook among other actors (not just university researchers) who are increasingly recognising the need to develop their use of the social sciences, bringing together expertise and evidence across different disciplines thus enabling them to extend and develop their research networks (for example, FSA, 2010). The work shadowing scheme and placements facilitated by Relu have also helped to strengthen these links.

The Tyndall Centre has been very successful at building a community, which continues to function through collaborative bids and the Researcher Network. Initially a PhD network, the Tyndall Researchers Network has grown to become a well-established and effective network. An active programme of meetings, both in and across institutions, means that relationships across a range of research levels are facilitated, both formally and informally. Many researchers who are associated officially and

unofficially attend meetings and take part in events. The funding mechanisms and the Researcher Network have both worked to facilitate community building:

> *"[S]o that's actually another way that the community was built up, thinking about it in hindsight, was by, so OK, first of all we had these networks working together, the people who actually won the bid. But then they opened it out to everybody saying, this is the Tyndall Centre, these are our aims and objectives, this is the type of research we do. If you're interested, write a bid and see if it gets funded."*

Drawing on our international case study, an annual conference is held across IGERTs, with, for example, a poster competition among trainees. The IGERT website also has an opportunity for members of IGERT teams to link into groups. Most if not all IGERTs appear to include some sort of workshop or conference experience on their own topic, giving trainees networking and community-building experience. IHOPE is very much a product of networking and deliberate community building across disciplines and the development of its research plan sought input from across the international community. A three-year grant has supported annual meetings, with QUEST supporting travel of international participants to the US. CNH also encourages novel networking strategies: planned mechanisms include both virtual and face-to-face interaction and a Fellows program for students and junior researchers.

Most QUEST interviewees said their professional network had expanded as a result of taking part in the programme (more usual among junior researchers) but we did not find any researcher who had experienced a major change in their network. This might be explained by the fact that the QUEST programme and projects drew heavily on existing networks of people who already knew each other. It was the exception rather than the rule that they looked for and brought in unknown people from outside, especially at senior levels. At junior levels, postdocs and PhD students were recruited by the projects; mostly they were already known to the PI or a member of the team.

There was a suggestion that QUEST became a community more from an outside perspective than an internal one. Within the QUEST programme, affiliations appeared to lie chiefly with the institutions and departments where people were located. There was undoubtedly some identification with project teams, usually indicated most strongly as belonging to a particular PI's team, but there was less identification with either the programme as a whole or with an earth system community (see also **Section 3.3.2**):

> *"People did not join QUEST to become a community they joined because they were interested in the work"*

IAB's recommendation to produce a QUEST Handbook (distributed at the second annual science meeting) may have instilled in some a greater sense of community:

> *"It had everybody's information, the project, summary, the deliverables, timeline, all of the policy and plans and arguments and bits and pieces - so people had - just that sense that they had information and they were all part of a think tank book - started to make a bit of a community feel"*

In addition to such mechanisms, location of researchers in close proximity was, unsurprisingly, identified as a factor in facilitating interdisciplinary work:

> *"[O]ne of the things that does facilitate it [ID], is being somewhere where you are constantly being exposed to other disciplines"*

> *"It's not just about creating the spaces for ID, it's also about the quality of those spaces. That is very influenced by the institution you are working at"*

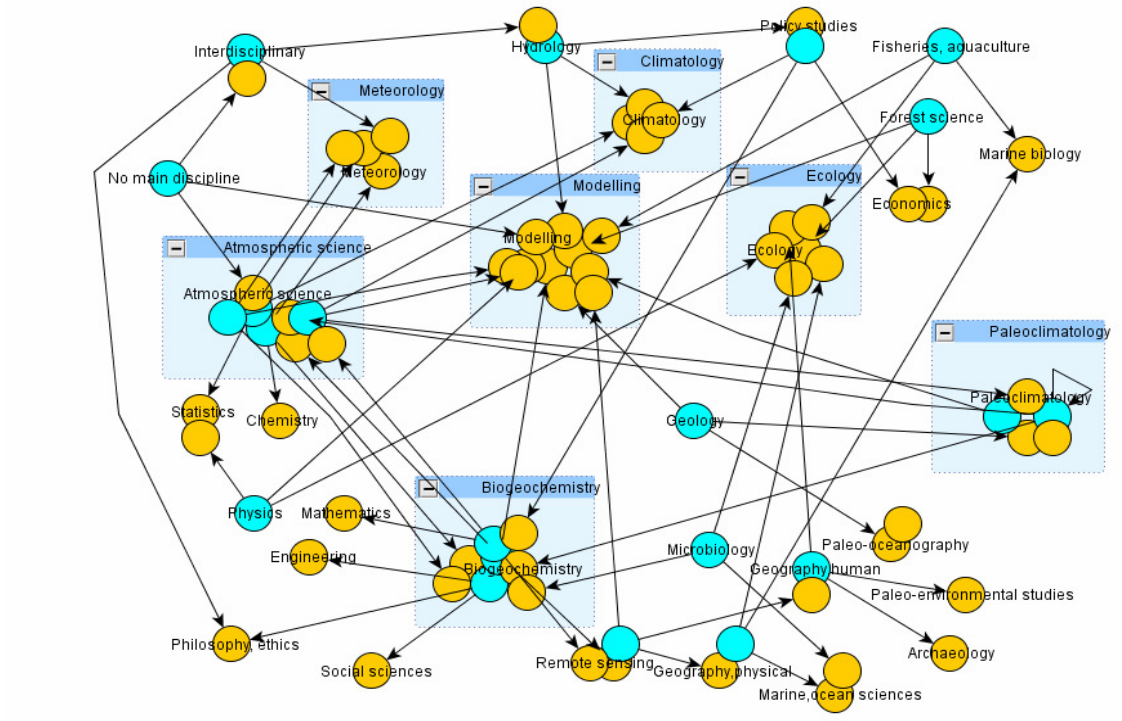
It was clear that community-building takes time to build up momentum and requires a degree of stability and continuity of funding:

> *"[T]he groups that have persevered and worked together now over these last two or three years are - we feel as though we've got a lot to offer collectively in the*

arena of the research that we're doing - so I think there may be many years of future collaboration ahead - which has been a good…outcome."

Across QUEST, there were a range of 'distances' evident, some intellectual, some geographic, that researchers were attempting to span. Intellectually, there were variable distances between disciplines but, as already noted, there were also distances between experimental scientists and modellers. Mapping the disciplinary relationships from the poster data gathered during the QUEST conference in May 2010 (**Figure 3**) shows some of these relationships. We asked "How interdisciplinary are you?" in order to map the links between disciplines represented within QUEST. Individuals were asked to locate themselves and their three nearest collaborating disciplines[8]. There was a convergence around modelling which was not surprising considering QUEST's agenda. However, none chose to identify him/herself as a modeller. People identified themselves variously with a discipline, subject or field of research even when most said that they did modelling; and there were a small number of people who pointed out that modelling is not a discipline but a tool. Nevertheless, in terms of collaborations, more people said they worked with modellers than with any other discipline or subject. What **Figure 3** indicates, in a simple form, is a mixture of mono-disciplines and integrated disciplines, with some interacting more than others. This gave a useful first impression which was later demonstrated in more depth by the bibliometric analysis.

Figure 3: Disciplinary relationships
Number of dots = frequency of occurrence; blue = ego; yellow = up to 3 collaborating disciplines



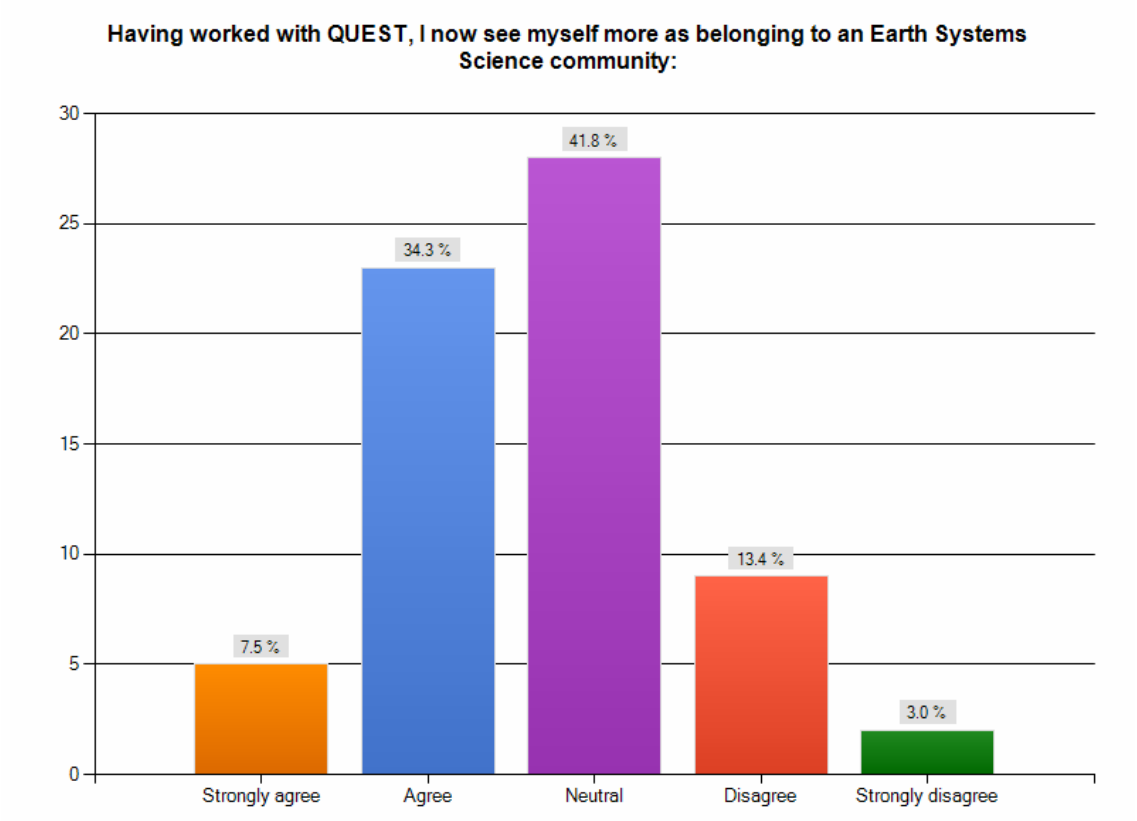
[8] Conference delegates were asked to indicate themselves (blue dot in Figure 3) and their three nearest collaborators (yellow dots in Figure 3) on a poster listing 40 disciplines. 22 people participated. The diagram was drawn by hand using a free software graphics program yEd Graph Editor and does not include any statistical analysis so, unlike the bibliometric analysis (described in **Annex 6D**), there is no significance attached to distances, and clusters only indicate frequency of occurrence.

3.3.2. An enlarged earth system science community?

In addition to interview data, we sought to explore in more depth this question of community-building through our QUEST survey and bibliometric analysis (see **Annex 6D** for details). We probed particularly on whether, having worked with QUEST, survey respondents saw themselves as belonging to and earth system science community (**Figure 4**) but there was parity between those who supported this statement and those who were neutral. In interviews, some were more positive:

> *"before, there were single figures of people trying to pull together different parts of earth systems in a joined-up way. However, with QUEST larger communities were created with PhDs and postdocs, and young people thinking in a systems way (so) that they have an actual belief that they can understand earth systems on a larger scale as a result of QUEST".*

Figure 4: Developing the Earth System Science Community

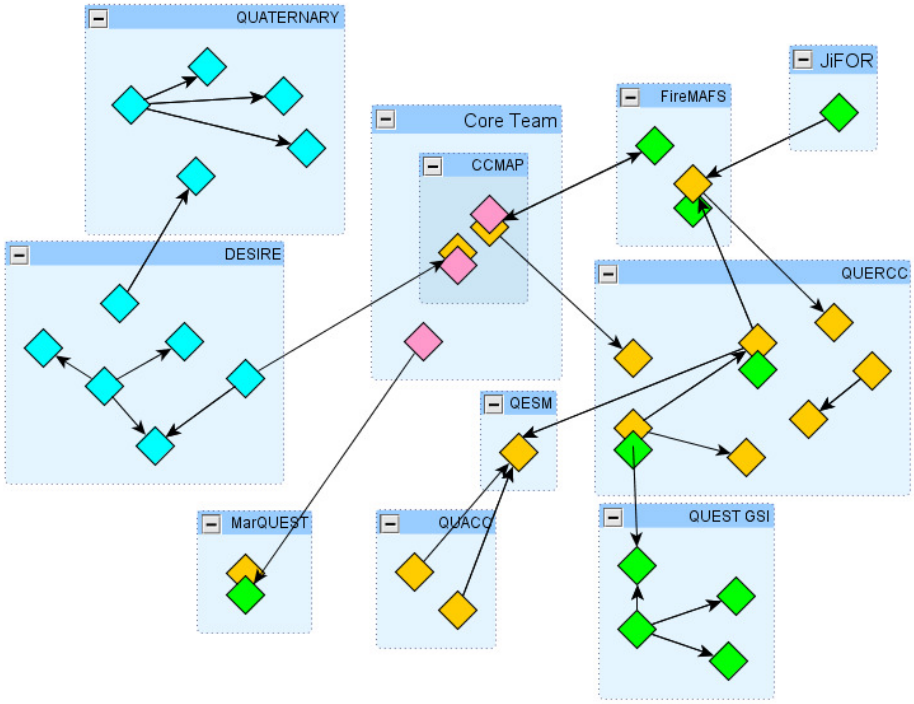


Using survey data, we mapped the relationships between 19 people across projects as shown in **Figure 5**. This highlights that people in Theme 2 worked very much within their projects, whilst there was some cross-over between Theme 1 and Theme 3 (although this relied to a great extent on PIs who were Co-Is on other projects). This mapping supports the findings of the bibliometric analysis (**Figure 7**)

Figure 5: Relationships between projects and themes within QUEST

Key
Diamond = individual person
Blue boxes = projects
Pink: member of core team
Overlapping diamonds = person involved in more than one theme

Yellow: Theme 1
Blue: Theme 2
Green: Theme3

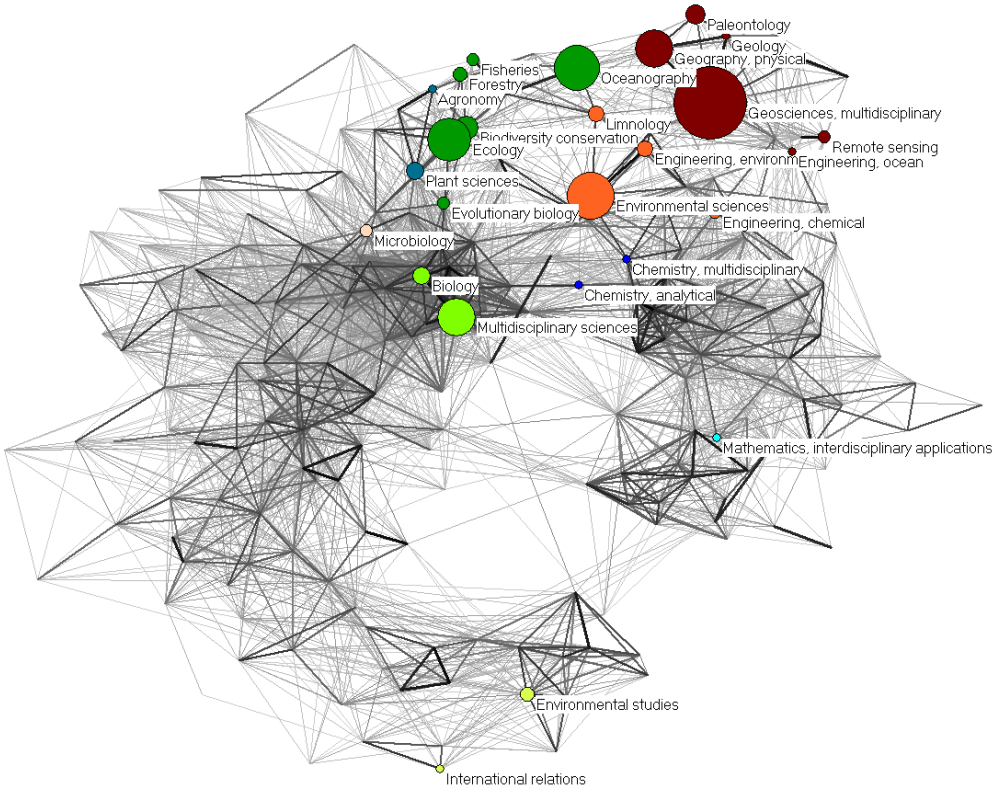


The bibliometric analysis shows that many QUEST articles have appeared in the disciplines of ecology, geosciences and environmental science and technology (S&T). Rafols and O'Hare note (**Annex 6D**) that many of the publications are in interdisciplinary Subject Categories (e.g. Geosciences Multidisciplinary; or Multidisciplinary Science) (**Figure 6**). There are few direct publications or references to basic natural sciences (biology, physics, chemistry) and in social sciences (although the latter was one of the objectives of the programme).

Each of the themes shows some diversity in its disciplinary composition:

- Theme 1 builds more on subject categories related to ecology
- Theme 2 builds more on subject categories related to geosciences and has a small but significant input from chemistry areas
- Theme 3 is perhaps the most diverse in that it has a more balanced distribution between ecology, geosciences and environmental S&T. This theme touches on many disciplines, with a small but visible interaction with the social sciences and mathematics. However, Rafols and O'Hare suggest that this larger diversity may be the result of lack of shared agenda and collaboration network in this theme

Figure 6: QUEST Publications (based on 196 publications)



The bibliometric analysis uses local maps to understand the internal structure of a body of research: co-citation maps to reveal the structure of research topics, and co-authorship maps to reveal to structure of collaborations.

References can form 'clusters' which reveal the dominant topics in the dataset, as articles on the same topic cite the same key references. The QUEST dataset shows seven main topics, each with different degrees of interrelation. The analysis confirms that the diversity of disciplines in QUEST is not the results of aggregating various mono-disciplinary topics. Instead the topics build on various combinations of the subject categories from within the Web of Science disciplines of ecology, geosciences and environmental science and technology (Slides 16-22, **Annex 6D**). For example, the subject categories for **Figure 7** blue cluster are oceanography, geoscience and environmental science; green cluster are meteorology, atmospheric science and geoscience; red cluster are geoscience, meteorology and environmental science.

The co-authorship map (e.g. **Figure 8**) shows how researchers are related to each other according to co-authored publications. The co-authorship network is divided among themes. One can observe substantial collaborations around Theme 1; a less dense network for Theme 2; and a lack of co-authorship in Theme 3. This may suggest that Theme 3 did not share a community or it may reflect the fact that it started later than the other themes and has had less time to achieve citations[9].

[9] Rfaols and O'Hare do, however, caution that, since Theme 3 only has 48 papers in comparison to ~100 for the other themes, we cannot rule out that such conclusion is an artefact of size difference. Further research would be needed to confirm this point.

Figure 7: Similarity of top cited references
Threshold > 5 times cited

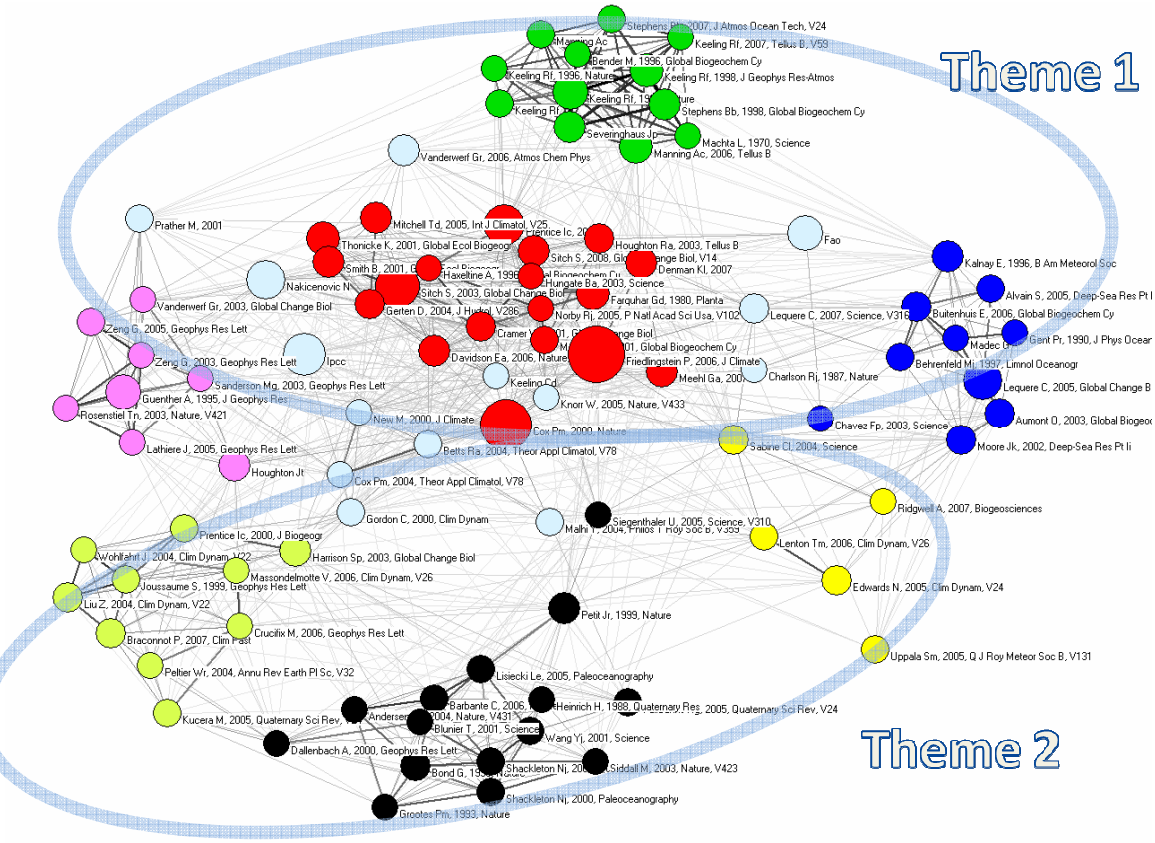


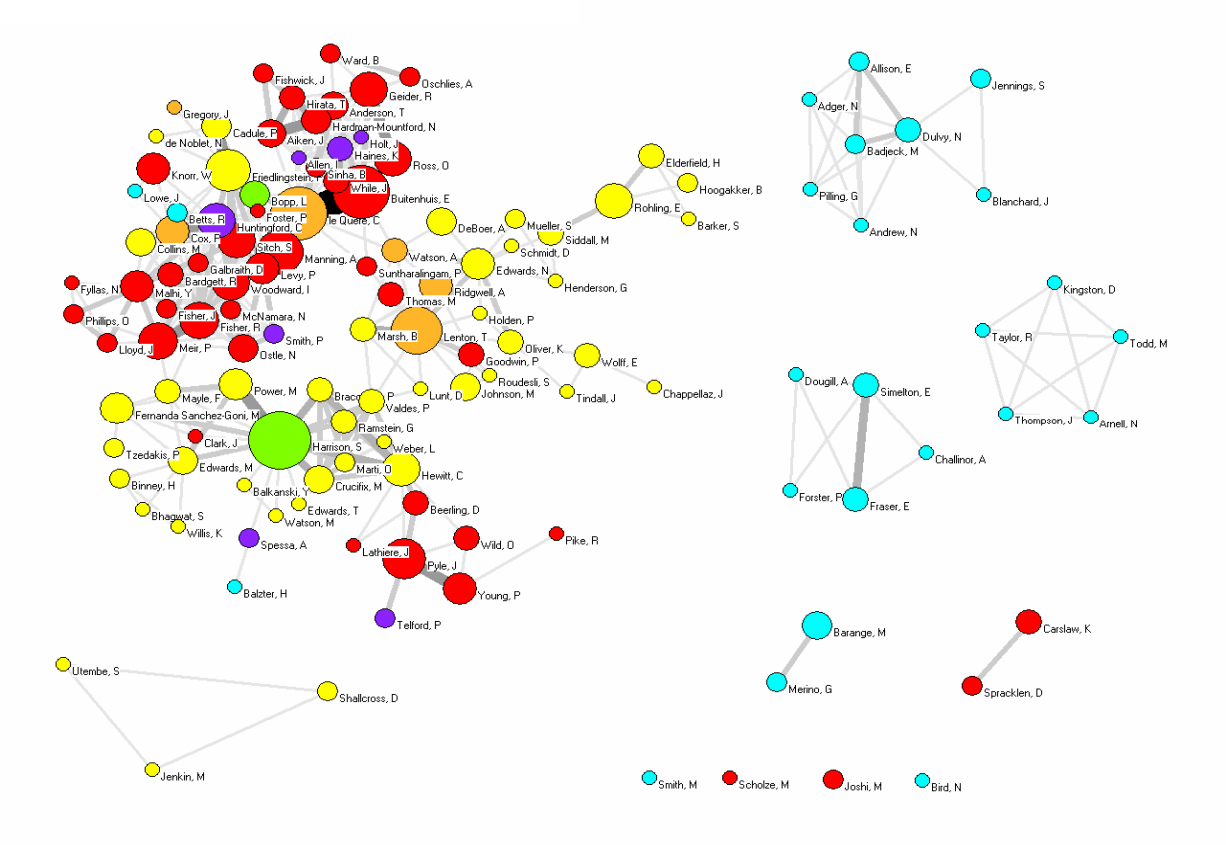
Figure 8 is different from the mapping produced from survey data (**Figure 5**) which shows people in Theme 2 as separate and some cross-over of PIs as Co-Is between Themes 1 and 3. What **Figure 8** shows is that there is a handful of people who form connecting nodes. In terms of 'community' this might suggest that researchers are not well embedded in an earth system science community which relies on the activities of a small number of individuals to make the connections.

As indicators of the degree of integration in earth system science both mapping and bibliometric analysis suggest that this field is building on several already evolved research specialities, and that it is an ongoing process. The disciplines mapping and the bibliometric analysis both show that the diversity of disciplines in QUEST is not the results of aggregating various mono-disciplinary topics (e.g. chemistry and law), rather it builds on subject areas that are already integrated subject categories or what we have termed elsewhere (see **Section 3.2**) 'portmanteau disciplines' or 'interdisciplines' (e.g. atmospheric science).

Figure 8: QUEST Co-Authorship

Key

Theme 1: Red	Themes 1+2 : Orange
Theme 2: Yellow	Themes 2+3: Green
Theme 3: Blue	Themes 1+3: Purple



3.3.3. Lessons for interdisciplinary networks

Encouraging self-reflection

We examined the lessons learned on developing interdisciplinary networks across the case studies. A strong sense of community-building underpins the Relu programme: effective research programmes need a community of people that are linked to, have benefited from, or potentially think they will apply for funding from them. This in turn leads to a cadre of peer reviewers. The Relu Directorate recognised that there was an obligation on them 'to pull something off' which reflected the interdisciplinary achievement and to create a new research community which had not previously existed.

From the outset, Relu actively promoted debate and discussions on interdisciplinarity, using a series of 'warm up' events in order to build networks, communities and capacity. Examples include a workshop entitled *People and the Environment: Scoping the Research Agenda* held in May 2005 to develop papers for a special issue of the *Journal of Agricultural Economics* (JAE) to put on record Relu's rationale and objectives. Throughout the life course of the programme, special issues have been seen by the Directorate as a key means of promoting interdisciplinarity (e.g. Phillipson, Lowe and Bullock (eds), 2009; Phillipson and Lowe, (eds), 2008). These special issues created external milestones which were seen as a key management tool by both researchers and programme leaders in order to deliver interdisciplinary integration.

A number of Relu-funded projects have been specifically reflexive about the interdisciplinary process. For example, Relu researchers conducted three workshops at the first Relu conference in 2005 as part of a project which examined processes involved in making interdisciplinarity work. A key finding from this research was that interdisciplinarity requires conscious effort, time and resources for the development of interpersonal relationships to enhance effective communication and thus successful collaboration (Marzano et al., 2006). Oughton and Bracken (2009) have reported on the significant differences in the ways that researchers establish and frame disciplinary, compared with interdisciplinary, research.

Some groups have inevitably been more reflexive about the interdisciplinary process. As part of the Relu project *Collaborative Frameworks in Land Management: A Case Study on Integrated Deer Management*, researcher Liz O'Brien (O'Brien, forthcoming) explored researchers' and stakeholders' perspectives on 'participatory interdisciplinarity' to identify the pros and cons of this approach and whether particular barriers or facilitators should be noted for the future.

Other examples of reflection include, for example, the Tyndall Centre's practice of encouraging individuals annually to place themselves on a "triangle" of (inter-) disciplinary self-definition. The various IGERT programmes report to NSF progress in interdisciplinary accomplishment on an ongoing, self-monitoring basis. IHOPE began with explicit exploration of what interdisciplinary collaboration could mean and this reflection continues as the programme evolves.

3.4. INFLUENCING NEXT GENERATION RESEARCHERS

In the long-term, interdisciplinary capacity-building will rest on the attitudes, abilities and career prospects of the next generation of researchers. Different case studies took different approaches, and placed different levels of emphasis, on influencing next generation researchers; some of which are illustrated in this section.

Ranging across fields and problems through over 250 large grants, the US NSF's IGERT (Integrative Graduate Experience and Research Traineeship) programme described in **Annex 6E** displays an outstanding commitment to the generation of a cadre of future interdisciplinary researchers.

Tyndall produced a cohort of researchers that has spread successfully into academia and many Tyndall PhD graduates have gone straight into lectureships, despite some qualms about whether their interdisciplinary training would equip them for such posts. Some of the work started at the Tyndall centre has evolved into other research centres, and those centres are being run by ex-Tyndall people.

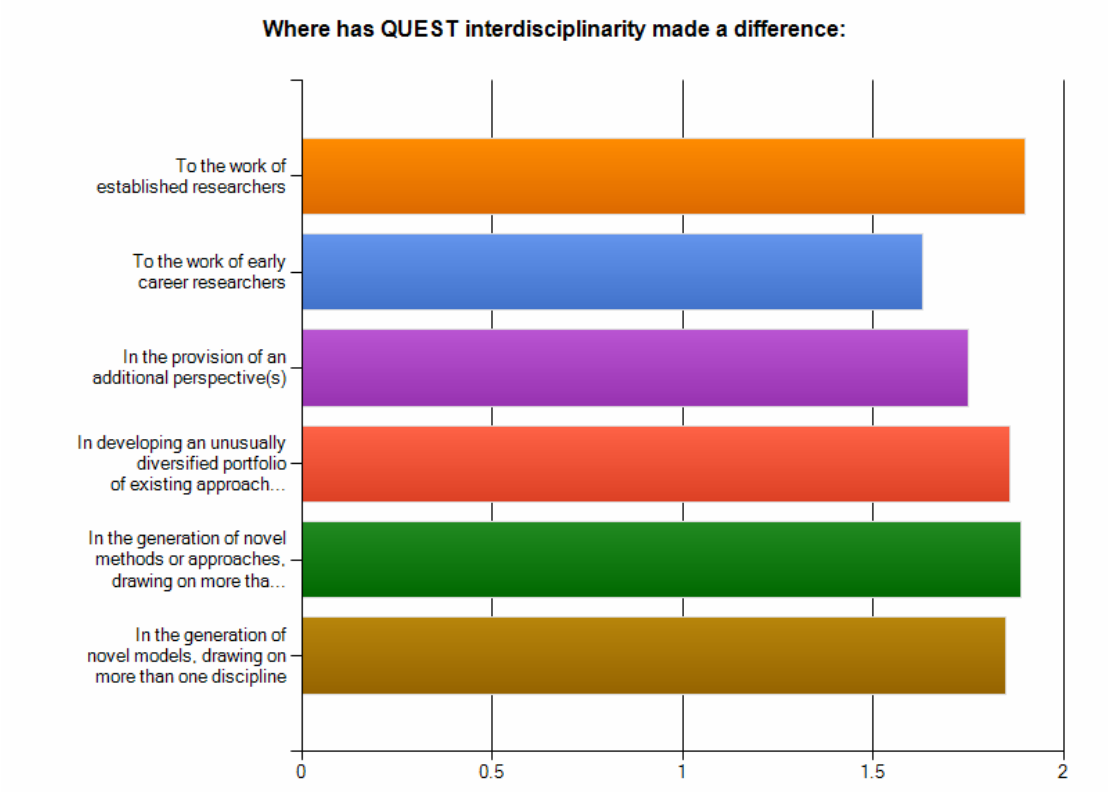
Relu has had a sustained focus on capacity building among ECRs, for example, commissioning Meagher and Lyall to run a workshop in January 2006 as part of the second Relu annual conference. The objectives of this workshop were to:

- help Relu provide a stable basis for younger researchers to continue interdisciplinary careers within and outside of academia
- identify for Relu: training needs, needs for capacity-building; and relationship of these to career needs of, in particular, younger Relu researchers
- help generate preliminary insights as to practical/tactical advice and lessons learned, covering issues such as publication strategies, training needs and career tracks

UKERC also has a number of initiatives regarding. The annual one-week summer school was apparently seen by students as a valuable networking opportunity with people who have similar difficulties in their research.

QUEST survey respondents suggest that the programme had slightly more impact on the work of established researchers than ECRs (**Figure 9**).

Figure 9: Where QUEST interdisciplinarity made a difference[10]



Many of the QUEST postdocs whose responses informed this study regarded themselves as interdisciplinary before they joined the programme, mainly because they had done PhDs in 'integrated' subject areas. All those interviewed felt that their range of interdisciplinary experience had been developed but many felt mildly frustrated that their network of peers had not expanded. Most of the postdocs said they came from different backgrounds to the fields they were working on in QUEST. They all said it was difficult in the beginning and that they had to work hard and do a lot of extra reading of unfamiliar journals to get a feel for the topic. Several of them had to learn about modelling, which they saw as an advantage for the future (e.g. "if someone can do climate modelling they can get a permanent job despite the recession"). Their day-to-day experience was of working on their own, often on a specific aspect of a system, so they themselves did not have to be interdisciplinary. Interdisciplinarity became more important when it came to model building. Some said it would have been good to have more contact with other postdocs, especially as, compared to PIs, they are the ones who have time to talk and teach each other. The postdocs largely enjoyed being part of QUEST and learned a great deal from working on the projects. Several respondents to this study who were at postdoc/PhD level said that support and help came informally from people who were not, primarily, part of QUEST.

In general, most PIs and senior researchers advise PhD students and ECRs to stay focused within their discipline, build up some expertise and publications before thinking

[10] Y axis labels in full: To the work of established researchers; To the work of early career researchers; In the provision of an additional perspective(s); In developing an unusually diversified portfolio of existing approaches and methods; In the generation of novel methods or approaches, drawing on more than one discipline; In the generation of novel models, drawing on more than one discipline

about doing any interdisciplinary work. They find it hard to recommend to a student they should go in that direction, venturing into interdisciplinary work too soon may make getting publications and a job much harder. Consequently, as one respondent told us "it's hard to find young scientists working on these interdisciplinary fields." while an ECR suggested:

> *"It's alright to be in the middle of the [Tyndall] triangle when you're some hoary old professor, who's kind of finished their research career and just wants to go to meetings from now on. That's fine, but in terms of carving a niche in the world, I don't think that's the place to be."*

On the other hand we were also told:

> *"I think I've got quite a lot of good experience and good contacts with quite cutting-edge science in climate science and things. So I think that's helped shape what I'm doing now and plan to do in the future"*

3.4.1. Lessons for interdisciplinary career development

Some of the advice that was proffered by QUEST respondents to this study, either through interviews or the survey, for those considering embarking on an interdisciplinary career is summarised in **Table 1**[11].

Table 1: Respondents' advice on interdisciplinary careers

On personal qualities

- Be aware of how you like to work – do you have a preference for working alone and contact with only one or two people or do you like working with a bigger group where different things are going on (if the former then ID might not be for you)
- Be prepared to talk to lots of people and ask lots of stupid questions
- Be prepared to know a lot about some things and very little about others
- Be willing to go a bit further than just learning the terms other people use
- Do you want to do interesting work or do you want to be famous? If you want to succeed as an academic you are much better off doing a narrow body of work and publishing around small topics, because then you can be the word expert in that thing and that's what academia rewards.
- Do what you find most interesting, because if you find your research boring it will be much harder to find the motivation and self-discipline to continue it

On professional development

- Get a couple of postdocs under your belt first with one particular discipline
- Get to know the people you will be working with before you commit
- At meetings and conferences use the coffee breaks, and talk to people at the bar – they are a great opportunity for meeting your peers and creating contacts
- Learn modelling, even if its only a little bit and you don't plan to use it
- To the social scientists – go for co-authored team writing
- Don't try and learn everything, because you can't, not to the level you need to work in research
- Be very clear about what you want to do, what your area is, what you are
- Meet face to face especially at the beginning to get to know each other
- Be curious and willing to challenge but be willing to listen
- Don't get hung up on the concerns about not having a discipline behind you
- Build up your personal skill base so that you have something to bring to an ID collaboration.

On PhD supervision[12]

- It is good to have supervisors from the different disciplines.
- It is good to have them together in the same room when making key decisions
- If they're coming from different disciplinary perspectives it is important that supervisors listen to each other, and they don't give contradicting advice
- If they do give contradicting advice, you need to all discuss it between you
- Have your subject matter reasonably well represented in terms of supervisor's specialities
- Don't feel you have to be drawn too much into one discipline or another

[11] Further 'lessons learned' drawn from across the case studies are presented in Annex 7.
[12] Further advice for supervisors of interdisciplinary PhDs is given in one of our short notes listed in the Bibliography in Section 5.

3.5. CHALLENGES OF INTERDISCIPLINARITY

Many of the challenges posed by interdisciplinarity, whether at the project or programme level, are pervasive and already well rehearsed[13]. Unsurprisingly, many aspects of our interviews, across all four of the UK case studies, followed a well-trodden path. So we heard about the challenges of maintaining one's identity and expertise, of trying to remain close to the state of the art simultaneously in more than one discipline but, above all, of maintaining one's university position, as illustrated by the following responses:

> *"if you want a position with a university, you have to have a discipline. This implies you have to have published in these disciplines and to shape your research in a way that will fit this discipline. But if you have an interdisciplinary research centre this allows for interdisciplinary research but they are funded on soft money and researchers are on short-term contracts"*

> *"universities require researchers to think in disciplinary ways, reward researchers for disciplinary thinking, put people in departments that require them to publish in disciplinary journals even if they are completely inappropriate for your research. The academic life is structured around disciplines, the research councils are structured around disciplines"*

A common interdisciplinary research management challenge across all of the case studies was that this activity takes time both in the sense of devoting enough time to the integration activities but also allowing enough time during the course of the programme for these to develop:

> *"there never seems to be enough time, there always seems to be too much to read. But those aren't obstacles; they are sort of, day-to-day…realities"*

> *"[interdisciplinarity] involves a lot more meetings rather than doing stuff"*

Some of the integrators whom we interviewed agreed that they did not spend much, or enough, time on this activity. Taking a 'core team' approach did not necessarily make this any easier; the QUEST experience was that it took quite some time (one interviewee described it as 'several years') before that group understood their integration role and were able to convey that across the programme.

So we already know that interdisciplinary isn't easy and that it doesn't just happen: it has to be planned for, developed and actively managed.

With its inherently multi-faceted and globally-based approach, environmental research reflects, and sometimes throws into sharp relief, challenges existing for *all* interdisciplinary research. Perhaps especially pressing for environmental research are those issues of scale, space and timeframe discussed earlier, along with a dynamic tension between what can be learned at a local level (e.g. a catchment) versus what universal conclusions can be drawn pertinent to the entire globe.

3.6. VALUE-ADDED THROUGH MANAGEMENT

3.6.1. The locus of responsibility

Interdisciplinary initiatives impose extra demands on leadership. An interdisciplinary leader needs to be inspiring, inclusive, capable of managing complexity, and be able to lead by example and promote integration across the programme. For large-scale interdisciplinary initiatives one would expect the programme directorate to act as an intermediary between the research councils and the funded researchers with a clear remit to drive interdisciplinarity across the programme.

[13] For a discussion of some of the challenges of interdisciplinarity see, for example, Lyall, et al. (2011), Klein (2010), Lattuca (2001), National Academies (2005).

One question that the four UK case studies throw up is whether this latter responsibility should be given to one person or to a team of people? If this responsibility resides mainly within one individual, how senior should this person be? Is this a primary role for the director or for a trusted lieutenant in the form of a dedicated interdisciplinary co-ordinator who is responsible for integrating across the research programme and for promotion of cross-disciplinary research? We have observed all of these models operating in the cases studied.

A further management question that arises is what role any programme advisory board will play in fostering interdisciplinarity. This will depend to a considerable extent on whether such a group has the relevant expertise, on whether they have a reactive or proactive role, and on whether their function is purely advisory or commands accountability from the programme leaders. This question of who holds the interdisciplinary integrators to account also extends to the research councils. Waiting until the end-of-award report to assess whether an interdisciplinary initiative has achieved its goals is too late; an effective science programme manager needs to hold the programme to account throughout its lifetime, for example, encouraging reflection or formative evaluation on an ongoing basis.

Management challenges are affected by the locus of interdisciplinarity (for example, the demands of management may differ depending on whether the core focus of the interdisciplinary effort is placed at the project or programme level) and also by context (e.g. one or multiple institutions, particular configurations of disciplinary cultures, expectations of funder(s) etc.)

A key finding identified by interviewees from across the case studies was the need to facilitate the integration process and set out interdisciplinary expectations very clearly right from the start of the programme. The senior-level focus group echoed the importance of managing expectations on all sides, including but not limited to those of funders.

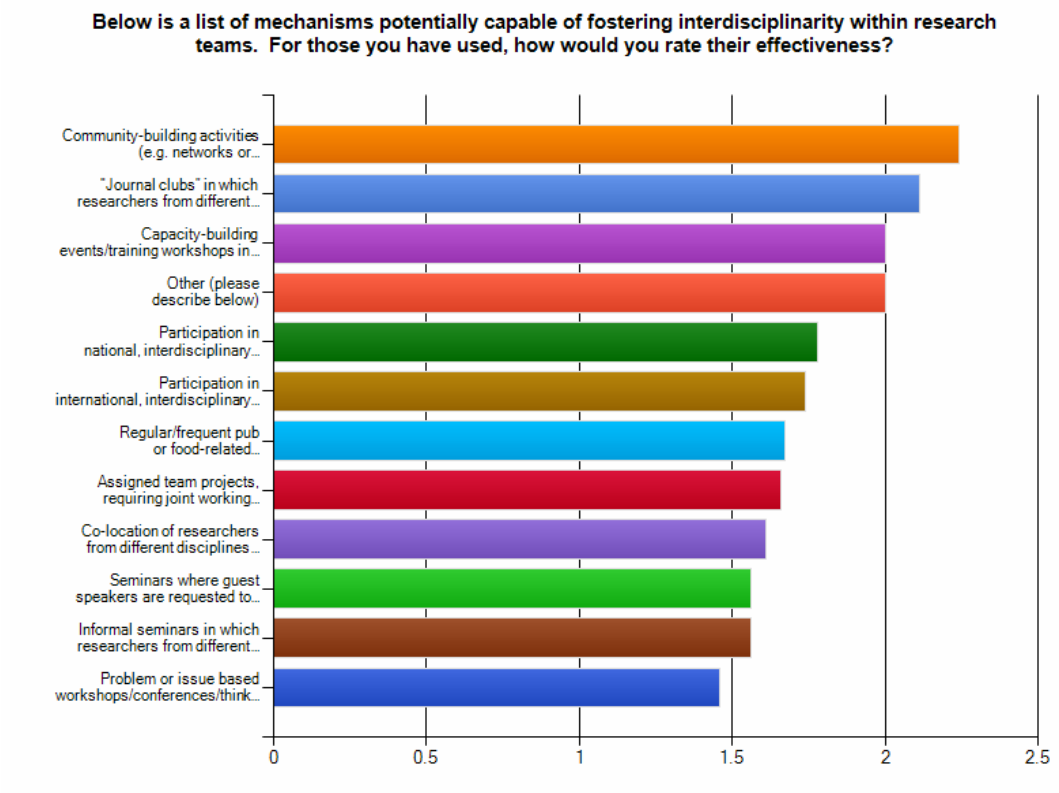
3.6.2. Mechanisms to foster collaboration

This active management of the interdisciplinary integration process can take a variety of forms. The Relu case study demonstrates that funding interdisciplinary 'warm up' activities can be key to developing such a culture. Seed-corn funding has an important role to play in catalysing interdisciplinarity and mobilising interest in a programme in order to engage diverse researchers. Such awards can foster new interdisciplinary research collaborations between natural and social scientists, for example, with a view, to strengthening proposals for larger research projects in subsequent funding calls. Specific funding modes can also be designed to encourage innovative higher risk/adventurous interdisciplinary research and to facilitate greater engagement of non-academic stakeholders.

A previous study (Meagher and Lyall, 2007) found that, at various stages (pre-award, award, post-award), a variety of linking activities were facilitated by Relu's seed-corn awards, including informal links and networks between researchers, and between researchers and other stakeholders. The scheme encouraged full-project bids to Relu, which in many cases appear to have been strengthened by the seed-corn experience. Although participation in this scheme did not give applicants privileged access in the subsequent wave of funding, it did appear to give a heightened chance of gaining funding in the second and third waves. Continuity of funding is then important in helping to build a community of people experienced in interdisciplinary practice.

When asked to consider a number of potential mechanisms to foster interdisciplinarity, QUEST survey respondents ranked community building activities as the highest (**Figure 10**).

Figure 10: Mechanisms to foster interdisciplinarity[14]



Ongoing linking activities are also important. These might take the form of cross-disciplinary meetings; visits/exchanges; cross-disciplinary interactions with stakeholders (such as Relu's workshadowing programme); the development of interdisciplinary publications and special issues. Mechanisms such as site visits by the director or research co-ordinating team to individual projects (as conducted, for example, by Relu and UKERC) and the annual reporting requirements are useful tools in encouraging researchers to think about both interdisciplinary integration as well as stakeholder engagement. This regular interaction allows for the identification of opportunities for interdisciplinary collaboration that can be further developed bilaterally or through workshops or the co-production of interdisciplinary publications. External evaluations of the programme as a whole, or individual component projects, may also help research teams and researchers to think about their role within the disciplines.

It requires a conscious effort to build an interdisciplinary programme. This process is most effective when it is encouraged rather than forced and demands well-developed management and negotiation skills on the part of the interdisciplinary integrators. This calls for a clear understanding of the complexities of the interdisciplinary process but also a good dose of realism. It requires a strong interdisciplinary vision on the part of the programme director but also a clear understanding of how to take the community with you so that interdisciplinarity lies at the heart of such programme and is not simply an add-on. The research councils also have a role to play. Shadowing the performance of Relu was a team of officers from each of the three research councils, which used to meet, at least initially, on a regular, possibly monthly basis. In many respects, these officers were the guardians of interdisciplinarity, ensuring that each Council's interests were represented within the programme.

The strategy for achieving interdisciplinarity may evolve as the programme develops. So, in the early years, the focus might be on running events organised by the

[14] For a full listing of Y-axis labels see **Annex 6D**.

programme directorate then, as the programme matures, shifting the focus to stimulating others in the project teams to run such events. Those tasked with interdisciplinary integration need to put effort in to encouraging the project teams to think for themselves about other forms of cross-cutting activities, not just events, in order to pull together different projects or themes across the wider programme. This helps to build linkages across projects and make a programme 'more than the sum of the parts'.

The practice of disbursing funds in consecutive rounds appears to reinforce the process of building interdisciplinary expertise and capacity across a programme. This was apparent from the Relu and UKERC case studies but is less evident in QUEST where the majority of funds were awarded at the beginning of the programme with only Theme 3, the 'social theme' coming on stream later once the programme was established. The timing of the inclusion of the 'human aspects' into the programme made it problematic both in terms of conceptualisation and integration for people 'on the ground'. Bluntly, if the process involved in shaping an intentionally interdisciplinary programme does not include all the relevant actors from the outset, then one cannot hope to achieve an organisational structure that reflects and encourages interdisciplinary goals.

Both Relu and Tyndall used a variety of forms of active management and consecutive funding to good effect, for example:

> *"It was a big advantage at the beginning that they in the leadership of the Tyndall Centre were able to say, we like this idea but you need some better social science. In other words, they could talk to the people bidding for money from within the Tyndall Centre and help them improve their plan. So they felt it was important it was not a one-off grant programme, it was absolutely critical the process through which we could encourage people down the interdisciplinary route. This enabled us to create a number of projects that were interdisciplinary"*

However, for Tyndall this continuity of interdisciplinary effort was impeded by changes to Research Council funding:

> *"[O]ur experiment couldn't really carry on. What happened was, we had to then hunker down and shrink back to a core Tyndall again, we couldn't be as inclusive and as open as it was the original intention."*

3.6.3. Lessons for interdisciplinary leaders

When "lessons learned" for leaders were gathered from across case studies and the senior-level focus group, the vital importance of pro-active management was underscored repeatedly[15]. Many focused on the critical, early stage of an initiative. This stage includes problem definition, the selection of appropriate team members, and the designing of an initiative in which everyone has responsibilities and potential "wins" (including stakeholders, as appropriate).

Key messages for the *early* stage included:

- develop an appropriate focus, within an informed definition of genuine interdisciplinarity
- select the right people for an interdisciplinary team
- plan
- incorporate stakeholders early, if solving a problem is a goal

Other messages focus on the effective conduct of an initiative throughout its lifetime. Many of these lessons reiterate widely-acknowledged elements of any successful team – communication, trust, sound relationships. Others cite the urgent need for

[15] These lessons are expanded upon in Annex 7.

interdisciplinary initiatives to take extra time and make extra effort. Many messages fall under the rubric of effective, appropriate, practical management while others, generate an ideal of a step beyond 'management' into 'leadership'. Effective leadership can elevate individuals and disciplines into a genuinely shared vision and will significantly influence the 'value-added' of an interdisciplinary initiative.

Messages for management and leadership *during* an initiative tended to emphasise:

- developing communication and understanding
- using effective mechanisms for relationship-building, teamwork and networking
- recognising the time and effort interdisciplinarity takes
- managing effectively
- acting as a leader; set a tone and develop a team culture that fosters interdisciplinary research and capacity-building

3.7. INSIGHTS FOR FUNDERS IN THE FUTURE

Interviewees and QUEST survey respondents provided lessons learned in the form of messages, advice or recommendations for funding bodies aiming for added value through interdisciplinary research.

3.7.1. Ensure both focus and flexibility

Funders play a critical role in stimulating interdisciplinary initiatives. Ideally, in many respondents' eyes, the number of programmes that mandate interdisciplinarity would grow, particularly as complex problems become more pressing (as in the case of many environmental issues).

This entails funders identifying a focus which needs an interdisciplinary approach in order to be tackled effectively and asking questions that require individuals to work together across disciplines. Funders can play a truly catalytic role, for instance when problems are just beginning to coalesce. Even as funders frame a problem or area to be addressed through interdisciplinarity, however, they are encouraged to remain flexible, refrain from being too prescriptive and to take risks when asking for something new:

> *"Interdisciplinarity is about the process of creativity so that a true success in interdisciplinarity would always result in something innovative and creative, and surprising."*

3.7.2. Evaluate interdisciplinarity appropriately

Perhaps the most heartfelt and widespread subject for recommendations to funders from across the case studies and the senior-level focus group was that of appropriate evaluation.

At multiple critical junctures, the view persists that evaluation of interdisciplinarity needs to be tailored appropriately. Individuals are not asking for an easy ride, but do not want to be penalised for proposing interdisciplinary approaches which, by definition, are unconventional (even threatening) to individuals ensconced firmly in disciplines. Certainly, a great deal of funded research will and needs to be discipline-based, but the system is seen to work against the inclusion of even the most rigorous interdisciplinary work.

In fact, some would remind funders that it can be harmful to standards of genuine interdisciplinarity if everyone is allowed to receive interdisciplinary funding:

> *"So many things are supposed to be interdisciplinary and they're marketed as interdisciplinary. And to be honest it gives interdisciplinarity a bad name. It can be everything to everyone when it isn't really. And therefore, make funding available*

for it, and if things are coming in that aren't interdisciplinary and it's supposed to be an interdisciplinary call, then don't fund it."

Ideally, multiple funders investing in the same interdisciplinary programme would model good interdisciplinary collaborative practice among themselves, with good communication, equal ownership and gradual development of a shared view.

Peer review processes are cited repeatedly as a serious problem for interdisciplinary proposals:

"Change review processes! This is a big frustration…. You send in proposals and you get reviewed by disciplinary specialists. The more interdisciplinary you try to be, the more of a risk you run that one of the disciplines' reviewers might not like it. …You need the reviewers to be interdisciplinary."

Until a certain level of interdisciplinary capacity is built, peer review represents a chicken and egg situation:

"Interdisciplinary reviewers will only come about if there are successful interdisciplinary scientists who become reviewers, but they only become successful interdisciplinary scientists if they get a lot of interdisciplinary work funded and done, but that can only get funded if there are interdisciplinary scientists (as reviewers)."

A key step recommended for addressing this issue is to channel support explicitly to interdisciplinary work, by establishing either dedicated interdisciplinary programmes and/or a pool of money available only to highly interdisciplinary proposals, particularly as trying to get interdisciplinary research funded in the general call for proposals is seen as problematic.

Composition and management of review processes needs care. One suggestion was to provide training for Research Council programme staff, so that they are more able to deal with such issues and to distinguish genuine interdisciplinarity. Other suggestions include the straightforward but vital alignment of goals and criteria as stated in calls for proposals, with instructions for reviewers and panels. Selection of panel members is important, including individuals experienced in interdisciplinarity. Even with such people on board, a recommendation is to take time at the beginning of a panel meeting to develop common understanding of the programme and criteria by which interdisciplinary bids are to be judged.

End-of-award evaluation of interdisciplinary large-scale investments needs to be appropriate. While strong publications will be sought as measures of academic rigor, other less tangible indicators might suggest that added value from the interdisciplinarity is (or is not) being achieved:

"…if you have a set of papers five years in, which pay lip service to the complex questions but then quickly drop back down into fairly traditional disciplinary stuff, it's failed…You may not be able to answer the questions yet but you certainly should have connected some disciplines and made some progress toward those questions, and really show that you've built capacity…that probably (is) at least as important as the publications. If you see, for example, in a core team that those people are really thinking quite differently than they were three or four years ago, and second of all that you're getting disciplinary people who may still want to stay within their discipline but they're engaging far better than they did at the beginning with people from other disciplines. Those are the sorts of things you look at."

Closely related to evaluation of programmes is the issue of longer-term organisational learning among funders. It was noted that a great deal of tacit knowledge about management of interdisciplinary programmes can be held by Research Council officers, but unless that people-embodied knowledge is captured systematically, continuity can become an issue.

3.7.3. Provide strategic funding over time, and structure appropriately

Interdisciplinary research takes time to evolve; therefore funding bodies need to allow more time and more resources for interdisciplinary projects and programmes.

> *"You've got to give resource for people to meet and spend time together and work these things through. You're not going to get the same amount done for the same money. You know, it's tackling wicked problems and that takes more…co-production of knowledge is more time-consuming."*

Furthermore, long-term funding can have an impact on community and capacity-building. Related to this issue of time, suggestions to funders include providing funds for: seed-corn support, "warm-up" activities, development of tools and visualisation for policymakers and other users, follow-on grants to fund projects and support emerging collaborations. Awareness of necessary people dynamics is encouraged:

> *"When people are from different traditions, bringing them together physically is really important. You need to let them get past 'My field does this or that'"…. "A conference that may look like a junket is really much more important"*

Some flexibility in a programme's budget allows not only evolution but also an opportunity for the leaders to develop ways to facilitate genuine interdisciplinarity.

Another cluster of practical messages has to do with how funding is structured to best encourage interdisciplinarity. As noted above, programmes or funding "pots" dedicated to interdisciplinarity can be very helpful, or perhaps necessary, in ensuring that interdisciplinary work does not fall at the first review hurdle. Cross-funder (e.g. multi-research council) programmes can provide incentives for multiple research communities to participate.

3.7.4. Encourage engagement of stakeholders

At one level, funding bodies are encouraged to consider what role they, themselves, play in establishing the architecture of an interdisciplinary programme (for example, choice of leader, location, streams of funding, to whom it is accountable). If genuine policy relevance is sought, explicit acknowledgement by funders at the beginning can legitimise researchers doing things differently in terms of engaging stakeholders from the start, in order to avoid the phenomenon of "just natural science plus communication."

Individuals who can handle interdisciplinarity may be valuable resources for generation of impacts, not simply because of problems they may choose to tackle but also because of their abilities:

> *"When considering the impact agenda, bear in mind that the skills that enable academic researchers to communicate effectively with other disciplines also equip them to communicate with wider audiences."*

Indeed this ability to work with others having diverse perspectives can bring about a whole new level of "interdisciplinarity" by genuinely including stakeholders and the contributions they can make. Some would argue that the capacity to integrate across disciplines leads to a realism that is key to making a difference beyond academia, and that not only academics but other knowledge intermediaries have roles to play.

> *"If you want to be more realistic, you want to be more interdisciplinary. If you want to be deep (in understanding something completely), then you become more disciplinary. For politicians, it is useless to have the disciplinary approach.…Sometimes good consultants are underestimated. Good consultants work in a synthetic way…Maybe they don't push forward (an area) but they translate information from many areas to solve problems."*

3.7.5. Build interdisciplinary capacity

Finally, perhaps the most overarching role for funders is conveyed in a cluster of messages about building interdisciplinary capacity. Conventional academic structures, review processes and reward mechanisms are based on disciplines, setting up real barriers for interdisciplinarity. As relationships are able to be developed over longer periods of time, greater understanding develops across disciplines so that more opportunities for interdisciplinary research can be identified. Whether in a particular research area, or across the academic landscape generally, building interdisciplinary capacity will take time.

To increase capacity among those who are currently established researchers, certainly an increase in calls explicitly specifying interdisciplinary research would be appreciated. This might lead to some innovative thinking about structures and funding streams (such as changes beginning to be seen with cross-Council programmes such as Living with Environmental Change). Funding of interdisciplinary research is key but career paths are uncertain for interdisciplinary research and need to be addressed if capacity is to be grown:

> *"Address the lack of career progression for interdisciplinary researchers who are less likely to obtain tenured university positions but who may have valuable expertise that is worthwhile keeping."*

Even in the short-term, researchers with the potential to work across disciplines may need extra encouragement and resource to play an integrative role within an interdisciplinary team:

> *"You need a group of people whose job it is to really work on the integration…people who can work across those disciplines… And those people are still hard to find…start to nurture those sorts of people, give them a role, give them support…so that it (isn't) done on a Saturday evening at ten o'clock because these people are all off doing their disciplinary stuff during the day."*

Developing next-generation researchers is a key issue, especially if Research Councils wish to develop interdisciplinary capacity. Some messages related to interdisciplinary PhD training (e.g. breadth of PhD topic, relationship to interdisciplinary centres or schools, and exposure to different research methods), along with considerations as to context (i.e. interdisciplinary programmatic teams or standalone studies). One pragmatic recommendation was for more money to be available for training in various methods (from different disciplines) at intervals throughout a PhD.

Beyond the training stage, the issue of career progression is vital if funders are serious about building capacity in a more long-lasting and substantive way than "simple" production of interdisciplinary PhDs. When considering career possibilities, funders need to be aware of the constraints imposed by universities, with the suggestion that Research Councils (and universities) provide more recognition for ECRs and PhDs who take on interdisciplinary work, urging that interdisciplinary researchers should never be considered 'second tier'. Closely aligned with recognition is the conventional academic currency of research support; clearly, guaranteeing that funding would be available for interdisciplinary work: funders need to play more of a pro-active role if they want to make the future academic landscape more inclusive of interdisciplinarity.

4. CONCLUSIONS AND RECOMMENDATIONS

4.1. SUMMARY

What the foregoing discussion tells us is that interdisciplinarity can be a goal and an endpoint but it is also a *process* which takes place over time. Interdisciplinary funders and leaders ignore this at their peril. Interdisciplinarity rarely happens spontaneously or in a short time frame: it has to be actively sought and managed from the outset. This requires leadership as well as careful consideration of expectations and the examination of some basic epistemological and methodological questions. Interdisciplinary integration has to be catalysed, planned and continuously revisited: it is unrealistic to postpone integration until the end of a project or programme because researchers within the team will have been asking different questions in different ways. This situation may be exacerbated when model-building is the core integrative activity. Successful programmes are mindful of this process and build capacity by allowing for evolution through successive funding phases and by incorporating mechanisms for self-refection and learning.

We used a form of strategic mapping to help synthesise our findings across the five case studies (**Figure 11**). This leads us to identify five key success factors (**Figure 12**) for interdisciplinary programmes – locus of interdisciplinarity, catalysis, inspiring intellectual leadership, active management, learning and continuity – which we describe in the next section together with our recommendations for how these might be achieved.

Figure 11 gives a visual representation of these factors (identified by boxed text, numbered 1 to 5). This data visualisation technique allows us to manage the complexity of the findings by drawing perspectives together into one representation and to explore links between findings.

These five success factors rely on sub-factors discussed in **Section 3** and which are summarised as simple summary statements[16]. For example, active management (4) involves mechanisms to foster collaboration (17), integration (27), addressing issues of timing (25), encouraging the engagement of stakeholders (18), focus on policy relevance (26), building interdisciplinary capacity (19), recognising the value-added through management (28) and understanding the appropriate locus of responsibility (29). Similarly, catalysis of interdisciplinary research (2) can rely on interdisciplinary capacity being available (19), the use of mechanisms to foster collaboration (17) and opportunities arising where research domains are not well defined (15). Mechanisms to foster collaboration within these cases studies (17) in turn are influenced by encouraging self reflection (16), incorporating social sciences (14) and examining examples of effective interdisciplinarity (13).

Analysis of this simplified map of the success factors we had identified, using Banxia Decision Explorer® software, suggests that building interdisciplinary capacity and active management are particularly core issues. Both are linked to more factors than others considered (8 factors for each) and both are more central to all factors (both directly and indirectly) than others considered.

[16] Numbers at the front of the statements are added to aid navigation and are indicated in parenthesis in the following description (they do not imply any hierarchy of importance). Lines linking summary statements imply causal links between the statements, and arrows indicate direction of causality.

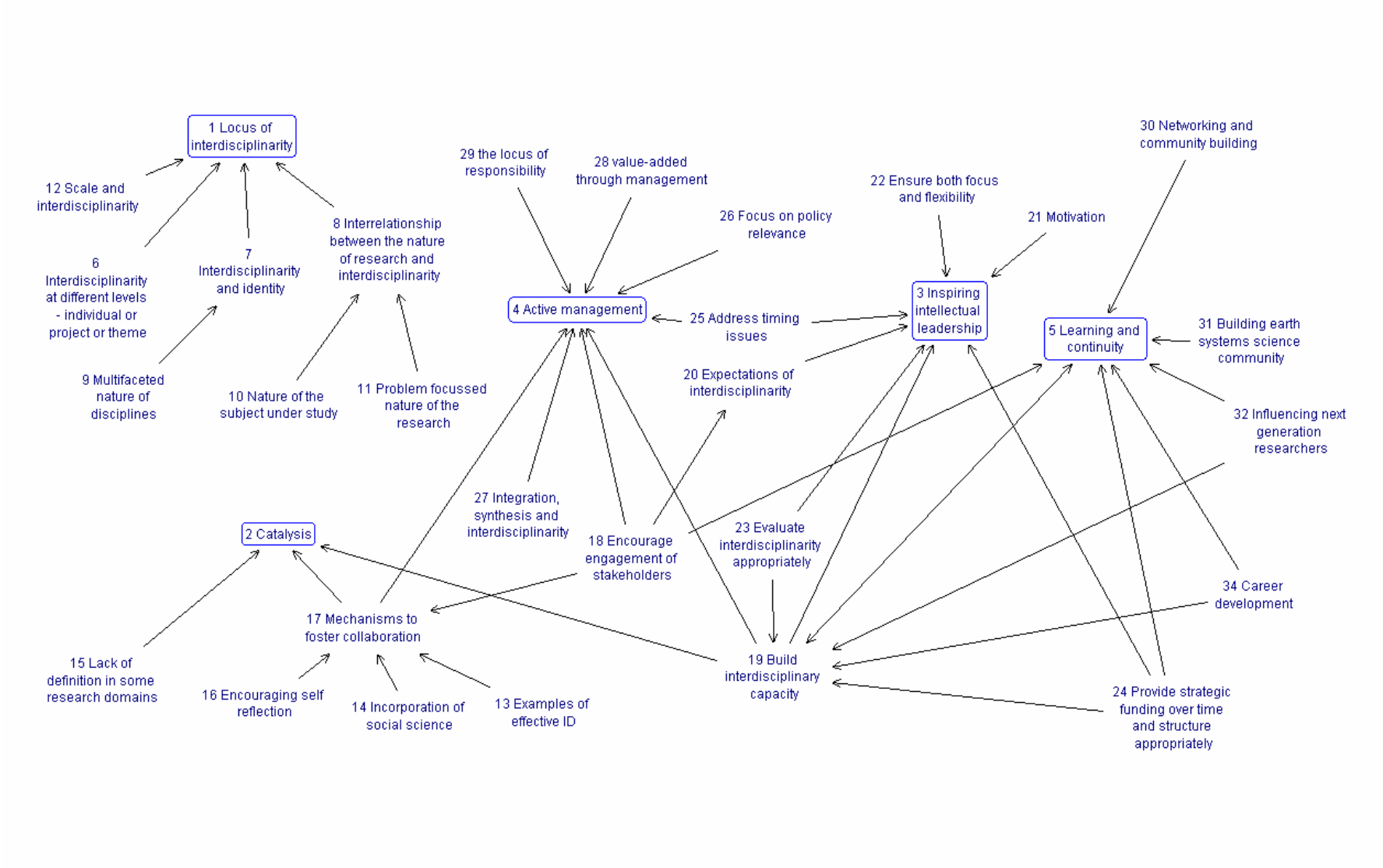
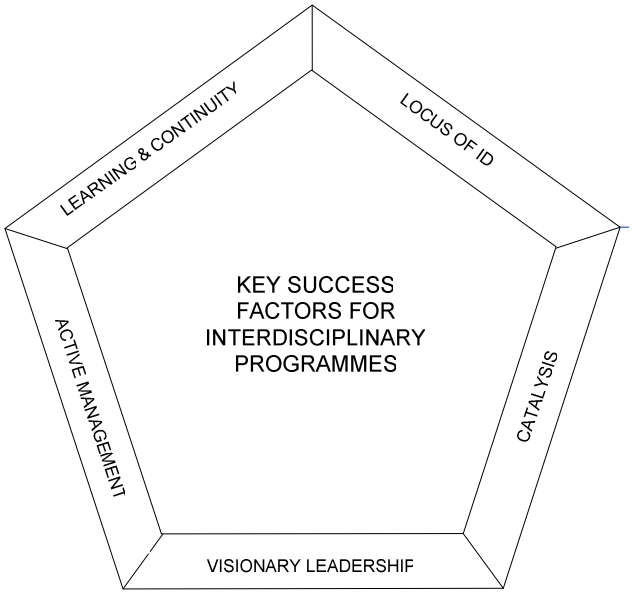


Figure 11: Synthesis of project findings

Figure 12: Key success factors for interdisciplinary programmes



4.2. KEY SUCCESS FACTORS AND RECOMMENDATIONS

Locus of interdisciplinarity

In designing an interdisciplinary programme, it is important to identify the locus of interdisciplinarity (e.g. at the level of the individual researcher, project, theme, programme) and to think through the implications of which level(s) are to be the chief platform for interdisciplinarity. This requires an examination of the epistemologies and ontological assumptions involved, focusing on where individuals within the programme draw their knowledge from and how this will impact on the locus of interdisciplinarity. In the case of environmental research, there may be particular tensions between universal and contextualised knowledge, between global and local scale, and between cultural differences where research is conducted on an international scale or with non-academic stakeholders.

> **Recommendation 1**: At the design stage of a large scale, interdisciplinary investment, consider the ramifications of interdisciplinarity if it is sought at the level of the individual researcher, a component project, a theme and/or at broad programme/ investment level. Pay due attention to contexts created by different institutions, cultures and funders.
>
> **Recommendation 2**: Research Councils constitute important drivers of interdisciplinarity and may wish to assess how their own structures and procedures reflect good practice, especially when interdisciplinary programmes require cross-council collaboration.

Catalysis

Interdisciplinarity takes place over time and proceeds through different stages. It is highly unlikely that integration will occur spontaneously at the end of a project or

programme unless deliberate steps have been taken to achieve this. Consider how best to tailor the design and implementation of such activities to a particular programme, whether, for example, seed-corn funding for small starter projects, early workshops and/or other activities might help to consolidate collaborations.

Recommendation 3: Develop early "warm-up" activities to lay the foundations for mutual understanding, communication, trust and sharing of responsibilities.

Recommendation 4: To ensure development of integration, support opportunities for interaction throughout the course of the grant. This may require additional funding and time for integrative activities and personnel.

Visionary leadership

Researchers need to be motivated, supported and engaged if they are to give of their best in what is, by definition, an unconventional, risk-taking endeavour. Consider the source of interdisciplinary leadership, whether it is provided, for example, by funders or by the programme director, or by a team of individuals in charge of component projects, and also how to use external advisory boards to best effect. Leadership is required to inspire diverse individuals on a continuing basis so that their individual motivations align with a common goal while simultaneously managing expectations to match feasible interdisciplinary outcomes.

Recommendation 5: Research Councils play an important role in shaping investments and on their longer term impacts. This requires an approach that balances focus and flexibility and a realistic understanding of what can be achieved within the timescales of a grant-funded programme. The effective and appropriate evaluation of interdisciplinary investments is a key area where funders could provide better leadership.

Recommendation 6: All directors of interdisciplinary investments should be supported through a peer-mentoring network with a particular focus on translating the vision into the practical reality of tackling the challenges of interdisciplinary initiatives.

Active management

It is important to recognise the demands posed by the process of achieving genuine interdisciplinary integration, and to identify responsibilities for various aspects of active management so that this is developed and maintained throughout the life of the grant. Management skills are not routinely taught to academics: while this issue may seem mundane in a monodisciplinary context, this skills deficit is attenuated when faced with the challenges of an interdisciplinary programme. The nature of this active management will vary depending on the locus of interdisciplinarity. Other questions to consider include whether one person or a team will manage the integration, and who – at what level of seniority – plays these roles (e.g. Leader, Liaison, Manager, etc.) at which points in the programme's development. Funders' support for active management is critical to achieving the potential value-added of interdisciplinarity.

Recommendation 7: Active management needs to be emphasised to research teams as vital for success and supported accordingly, for example by sharing organisational learning and providing funding for community-building activities.

Recommendation 8: Some form of formative evaluation should be encouraged for all larger investments to promote self-reflection and the appropriate evolution and development of research. Giving the director discretion to disburse funds in

phases during the course of the grant can allow adjustments to be made and facilitate the development of interdisciplinarity.

Learning and continuity

Capacity-building in a variety of forms is critical to the growth and longevity of interdisciplinary research expertise in the UK. This poses challenges for funders, institutional research leaders and others to ensure that learning from past experiences of interdisciplinary investments becomes embedded within collective organisational memory.

This requires greater continuity – of research networks and communities but also of research careers so that future career options are available for interdisciplinary Early Career Researchers and their expertise is not lost at the end of a programme. This is not to imply that individual interdisciplinary investments should be funded in perpetuity but Research Councils do need to develop more realistic expectations of the time frames within which major change can be achieved: a five-year interdisciplinary programme alone cannot provide the silver bullet to solving complex issues. This requires continuity of funding – appropriately reviewed – over the long term.

Recommendation 9: Research Councils should continue to provide strategic funding for interdisciplinary research. This funding should be structured appropriately over time in order both to build interdisciplinary capacity over the course of a particular programme and to ensure continuity of funding for interdisciplinarity across the research community. This requires appropriate evaluation of interdisciplinarity at various junctures.

Recommendation 10: A new vision is required to promote organisational learning for interdisciplinarity within and across the Research Councils. RCUK might consider:

(i) the establishment of an interdisciplinary reviewers' college (consisting of individuals expert in a range of interdisciplinary areas) to address the common challenge of finding reviewers who are sympathetic to interdisciplinary research and understand how to evaluate it both rigorously and appropriately

(ii) establishing shared administrative resources for interdisciplinary investments with dedicated administrators experienced in the particular requirements of interdisciplinary research and research training

(iii) facilitating the development of a cadre of early career and more senior interdisciplinary researchers by hosting community-building events across different interdisciplinary capacity-building schemes and investments. An Interdisciplinary Funders Forum similar to the Environmental Research Funders Forum (now part of LWEC) or the UK Strategic Forum for the Social Sciences could promote shared learning

(iv) developing an Interdisciplinary Portal analogous to the current RCUK Knowledge Transfer Portal to co-ordinate and consolidate access by the research community to information about funding, training and other forms of support dedicated to interdisciplinarity.

4.3. PROGRESS ON IMPACT PLAN

Our Impact Plan anticipated that wider interest was likely from the following categories:

1. the broad community of researchers who seek to participate in or lead interdisciplinary initiatives
2. academics with interests in the nature of interdisciplinarity as a field of study
3. research funders across RCUK as they frame, assess applications for, manage and evaluate interdisciplinary programmes
4. stakeholders in policymaking and wider society who deal with complex issues, particularly global change, for which understanding of interdisciplinary integration would be helpful.

To maximise learning and the spread of project impacts from this study we designed a range of dissemination and impact generating activities. These are described in **Table 2** with an indication of our progress towards these objectives.

Table 2: Progress toward impact

Planned impact activity	Progress towards achievement
Masterclass/workshop, focusing on interdisciplinary leadership and the management and design of ID programmes	Held in Edinburgh 18-19 January 2011
Project report	Submitted to NERC 31 January 2011. If permission is granted, copies of the final report will be posted on NERC website and on our own ID Wiki
Presentations at UK and international conferences	Two presentations to date: European Association for the Study of Science and Technology (EASST), September 2010, Trento, Italy td-net Network for Transdisciplinary Research Conference on Implementation in Inter- and Transdisciplinary Research, Practice and Teaching, University of Geneva, 15-17 September 2010 An invited presentation will be given at the Royal Society workshop on Challenges in Policy Relevant Interdisciplinary Science on 7 March and two further presentations are planned for 2011 td-net conference and the 'Atlanta Conference', Sept 2011.
Briefings for Research Council officials and research leaders	Scheduled to take place in February 2011
Accessible, practical guidance, in the form of online briefing notes	In preparation following January focus group and workshop; to be completed by end February A series of blogs on the Innogen blog and an article on interdisciplinary capacity building scheduled for March issue of the EGN (ESRC Genomics Network) newsletter
One or more peer-reviewed journal articles	Invited to prepare special issue journal article following presentation at EASST conference. Second contribution to be published in proposed Innogen journal special issue on interdisciplinary capacity building

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