Exploring Interdisciplinarity

Summary report of DICE at the James Hutton Institute

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The **Developing an Interdisciplinary Culture of Excellence** (DICE) project was funded by the James Hutton Institute and the research undertaken between 2012 and 2014.

A team of researchers from across three of the Institute's science groups (Information and Computational Sciences; Social, Economic and Geographical Sciences; and Environmental and Biochemical Sciences) formed the research team:

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Kerry Waylen (Social, Economic and Geographical Sciences) helped us design the DICE research. Altea Lorenzo-Arribas, Biomathematics and Statistics Scotland (BioSS) helped us analyse survey responses. Colin Campbell (Director of Excellence), Bob Ferrier (Director of Impact), and Laura Meagher (Hutton Board) helped steer the DICE project throughout the research period.

Further information

Internet web site: http://www.hutton.ac.uk/research/projects/Dice

Intranet web site: http://dice.ac.uk (access for James Hutton Institute staff)

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Executive Summary

1.1 Rationale for the research

This report synthesises the main findings of the *Developing an Interdisciplinary Culture of Excellence* (DICE) project. The project aimed to improve our understanding of current levels of interdisciplinary research (IDR) within the James Hutton Institute and assess what was required to support an interdisciplinary culture of excellence.

The DICE project was funded through a James Hutton Institute seedcorn grant between 2012 and 2014. The project was carried out by a team of researchers from across three of the Institute's science groups (Information and Computational Sciences; Social, Economic and Geographical Sciences; and Environmental and Biochemical Sciences). The researchers used different methods (interviews, staff survey, and bibliometric analysis) to explore interdisciplinarity at the Institute, with a literature review informing the empirical work and contextualising the findings.

1.2 Research methods

A literature review was ongoing throughout the DICE project, and aimed to develop a framework for understanding how IDR can be practised on the basis of sound theoretical foundations for (i) disciplinary integration, knowledge exchange, and research production, and (ii) identification of IDR, and its evaluation.

Between March and November 2013, semi-structured key informant interviews were carried out with 15 senior Institute managers (all seven Theme Leaders, all five Science Group Leaders, and the three executive directors of science) and with six external stakeholders with policy, operational and commercial backgrounds. They provided rich insights into experiences with and understandings of interdisciplinarity, and made suggestions about how to enhance IDR.

The survey of James Hutton Institute staff (November 2013) aimed to capture scientists' understandings of what IDR is; levels of IDR at the Institute; and staff views on barriers, challenges, skills, and supportive conditions associated with IDR. This summary outlines our main findings.

1.3 Why practice interdisciplinary research?

An interdisciplinary approach is widely advocated by funders and end users of research as well as scientists, particularly to investigate complex problems. Such problems often involve (i) uncertainties in scientific knowledge, (ii) h an activities and interactions, and (iii) the political, economic and cultural dimensions of knowledge affecting research and its impact.

Yet customers want their needs to be taken seriously and results delivered accordingly. Companies look for solutions to their problems; policy makers and agencies are interested in policy-relevant research. Whether this is through disciplinary or interdisciplinary research is of less importance and interest to them (although many stakeholders see benefits from IDR). The Scottish Government's RESAS Division, a major funder of the Institute, is an exception and explicitly demands an interdisciplinary approach.

Stakeholder interviewees indicated that good research and communication in teams and within the Institute as a whole should underpin all research. Many of the interviewees' comments would apply to any good research project, team work and management, regardless of how many disciplines it spans. For them, the

quality of project management and communication determines the quality of the result; the quality of internal and external communication determines the outcomes (e.g. knowledge exchange, policy impact).

Senior Institute staff agreed that an interdisciplinary approach has many benefits, in particular for tackling big questions or complex research issues such as the environment. IDR enriches understandings and can reveal gaps in knowledge about a problem. It was also seen to fit in well with the ethos of the James Hutton Institute. However, they noted that interdisciplinary approaches may not be able to adequately address some in-depth questions.

1.4 What is interdisciplinary research?

While the term 'interdisciplinary research' is commonly used to distinguish this approach from disciplinary, multidisciplinary, and transdisciplinary research, it is also sometimes used to refer to the latter two and to team-based research more generally. Within the literature, integration of disciplinary knowledge and methods is a key characteristic used to identify and assess the extent of interdisciplinarity in research, and to distinguish IDR from these other approaches to research. Integration is measured by the extent of blending of disciplinary knowledge and research methods, and the conceptual and institutional distance between collaborating disciplines.

Among our interviewees, there was a general understanding of interdisciplinarity as referring to working across disciplines towards a common goal, and usually to respond to a 'bigger picture question'. However, for many interviewees that meant working between social and natural sciences; for some it may have been multidisciplinarity and for others transdisciplinarity. Several interviewees said that they saw no particular difference in meaning between these terms.

Institute staff survey responses showed a diverse understanding of interdisciplinarity. The majority (59%) understood interdisciplinary research as integrating different disciplines to work towards a jointly set objective, rather than working independently under a thematic umbrella, and not (necessarily) involving non-academic participants. Yet 21% understood IDR to include non-academic participants, and for 16% of respondents, research was interdisciplinary if different disciplines work towards a number of goals under one thematic umbrella. These different understandings influence the assessment of how much of their research individuals would label as interdisciplinary.

Survey findings showed no clear patterns of association between demographic and Institute-related variables (age, gender, science group affiliation and length of time worked at the Institute) and variables such as how respondents understand interdisciplinarity, levels of experience of IDR, whether they combined social and natural science approaches, and what proportion of their work is IDR. There was also no evident relationship between gender or age and attitudes to IDR.

1.5 How do we recognise interdisciplinary research?

Interviews with external stakeholders did not reveal much information about what kind of indicators they consider useful to recognise interdisciplinarity. They saw IDR as having "both scientific and user benefit" and "providing solutions to actual problems rather than parts of them." Hutton Executive interviewees agreed that there was no perfect indicator to tell if IDR was happening, but still believed that non-perfect indicators were better than nothing. Senior managers suggested that different disciplines working together is a basic indicator of whether a project or piece of research is interdisciplinary. In considering interdisciplinarity, they

distinguished disciplines not only broadly, ie across natural/social sciences, but also more narrowly, e.g. across disciplines such as chemistry-psychology, economics-soil science, biology-informatics, or disciplines within plant pathology.

We found that no single indicator identifies IDR; instead, a combination of different indicators is needed. Based on our respondents' views on indicators, IDR at the Institute can be recognised by:

- a diverse mix of disciplines involved, leading to different perspectives being considered and integrated;
- a shared understanding of the problem and jointly determined research questions;
- research questions addressing complex and 'real world' problems;
- effort invested in developing a common language across the team;
- on-going, preferably personal, two-way communication;
- trust and good working relationships;
- a tendency for tasks to take slightly longer than anticipated;
- a diverse range of outputs (single disciplinary and interdisciplinary academic papers, synthesis papers, non-academic outputs and events), with number and background of authors playing a minor role as an indicator;
- being funded by an IDR programme; and
- greater advances in knowledge, but possibly with less depth.

Many of these indicators relate to the process of carrying out IDR (rather than the output). Several indicators are difficult to measure quantitatively and instead require a descriptive approach (e.g. to 'measure' whether there is a shared understanding of the problem).

1.6 How can we do interdisciplinary research better?

It is widely recognised in the literature that the processes involved in IDR are different from, and additional to, the processes involved in disciplinary research, ie research that does not involve integrating ways of thinking, knowledge, and research methods across disciplinary boundaries. Problems for IDR teams include resolving epistemological (beliefs about what knowledge is) and ontological (how to produce it) differences between disciplines. IDR team members need to spend more time to understand the problem to be addressed, and the different perspectives within the team; discuss and agree a research design; and sustain productive interactions during the project.

Some concerns were expressed about the difficulties that ontological and epistemological differences create for working together, and some suggested such differences may result in members of the team being less likely to communicate with each other effectively, or being less able to air their views confidently. Survey respondents also showed a considerable degree of awareness of the challenges and benefits of IDR, along with awareness of the personal attitudes, skills, and wider conditions needed to support this type of research.

Increasingly, the literature refers to social learning and effective knowledge exchange within teams as key to producing knowledge through interdisciplinary collaboration. Much emphasis is placed on interpersonal skills – in particular of team leaders – as the basis of good interdisciplinary team work. Our review showed high levels of convergence around the principle of integrated working, with attention given to ways of

'harnessing' disciplinary difference and conflicts to provide new insights unavailable from disciplinary approaches to research.

1.7 What do supportive conditions for interdisciplinary research look like?

The literature stresses that institutional support is needed for IDR from funding bodies, and the organisation where research is carried out. Support entails recognition of the more resource-intensive nature of IDR processes, and their lack of fit with existing, disciplinary-based organisational structures and cultures. There is increasing interest in how research organisations can encourage and facilitate interdisciplinary working in the design of organisational environments.

A number of themes emerged from our research about nurturing interdisciplinarity through supportive conditions:

- time – it takes longer to do IDR and this needs to be recognised;
- team building and communication – team members need to be open-minded and receptive, and effective formal and informal communication needs to be facilitated;
- research cultures and working environments need to be conducive;
- physical spaces – appropriate workplace design can enable interdisciplinary working;
- incentives for staff and training and skills– IDR should be considered in career evaluations and early career researchers need to develop their own discipline; and
- research funding – is a driver of IDR.

1.8 How should we evaluate interdisciplinary research?

Throughout the literature it is widely acknowledged that evaluation of IDR is not yet well-established and still requires development. However, it is generally accepted that evaluation after project completion is insufficient, and that this should be ongoing during the research process. The literature refers to both qualitative and quantitative approaches, and mentions indicators such as: an appropriate focus for the research, with clear rationales for disciplinary input; appropriate collaboration of disciplines; quality of team interactions; evidence of IDR capacity building; quality of team leadership and research management; institutional support; and evidence of integrated work.

Interviewees found the question of indicators for evaluating IDR difficult to answer. Their responses often related to definitions and benefits of interdisciplinarity, as well as the skills, attitudes, and conditions that enhance interdisciplinary working. These responses suggest that evaluating the process of IDR is equally important as evaluating the output from that process.

From a funding body perspective it is acknowledged that evaluating IDR proposals is a challenge, in particular since a panel may consist of reviewers from one or just a few disciplines which could not adequately judge (large) interdisciplinary projects.

Although endpoint evaluation remains more common, the literature indicates that evaluation should be part of the research design, and involve IDR teams from the outset. Focusing on ongoing evaluation by research teams themselves allows for social/collective learning and process adjustment.

1.9 Conclusions and recommendations

To understand and assess IDR at the James Hutton Institute requires clarity about our conceptions of this approach at institutional, science group, Hutton theme, project, and individual levels. We infer from our findings that there is not yet sufficient clarity about interdisciplinarity to identify levels of IDR robustly. We used a working definition in the survey which yielded results that can be used as a baseline, but in absolute terms these results can be contested. The Hutton institutional structure already promotes and supports IDR in some ways (e.g. research themes, interdisciplinary teams), and perhaps more than many other research organisations. More effort at all levels is needed to enhance both the Institute values and a working culture that is conducive to IDR; we provided an extensive list of suggested actions which can be taken forward by individual staff, research teams, and Institute management.

We recommend that the Institute agrees on and commits to an operational definition of interdisciplinarity that makes sense to staff, customers and stakeholders. This definition should acknowledge broad and narrow interdisciplinarity, ideally naming example disciplinary collaborations that are counted as interdisciplinary, and agreeing on indicators to measure IDR, even if these indicators are only second best (such as cross-disciplinary authorship). We recommend repeating the survey at regular intervals to monitor trends in interdisciplinary working.

Conclusions, in the form of recommendations for the Institute, were condensed from the DICE team at the end of the project. These were grouped into four areas:

- the time required to plan and do IDR;
- opportunities for discussion (formal and informal) and sharing experience/ knowledge;
- support for IDR from the Institute's management structure and processes, including training; and
- awareness that IDR depends on excellent project design, leadership and management.

Communication is linked to and important for all of the four areas.

2 Research objectives and methods

This report summarises the main findings of the *Developing an Interdisciplinary Culture of Excellence* (DICE) project. The project aimed to improve our understanding of current levels of interdisciplinary research (IDR) within the James Hutton Institute and assess what was required to support an interdisciplinary culture of excellence. DICE was funded through a James Hutton Institute seedcorn grant between 2012 and 2014.

Our primary aims were to improve our understanding of current levels of interdisciplinary research (IDR) within the, and assess what is required to support an interdisciplinary culture of excellence.

The specific objectives of the DICE project were to:

1. synthesize lessons learned from leading international institutions, organisations, and initiatives on interdisciplinarity, from academic literature, grey literature, experts, and initiatives to promote interdisciplinary research and synthesis.
2. explore existing understandings, attitudes, and perceived views of practices and challenges relating to interdisciplinarity, and identify opportunities for greater levels of interdisciplinary working at the James Hutton Institute.
3. disseminate our findings within and beyond the Institute.

To achieve these we used both quantitative and qualitative social science methods (semi-structured interviews, online survey), and carried out a literature review and a bibliometric analysis (Table 1).

Table 1: Objectives and methods used in the DICE project

Objectives	Methods
1. Synthesize lessons	
• To synthesize lessons learned from leading international institutions, organisations and initiatives on interdisciplinarity, from academic literature, grey literature, experts, and initiatives	• Review and synthesis of current theory and practice on interdisciplinarity relating to socio-ecological systems • Informal discussions/interviews with experts
2. Explore interdisciplinarity	
• Explore understandings, attitudes, views of practices and challenges relating to interdisciplinarity, both internal and external to the Institute • Identify opportunities for greater levels of interdisciplinary working at the Institute • Investigate the demand for interdisciplinary research, in addition to the supply	• Semi-structured interviews with Hutton Science Group and Theme Leaders, Chief Executive, and Directors of Science • Semi-structured interviews with representatives of key external stakeholder groups (policy, commercial, agency) • Online questionnaire distributed to Institute research staff
• Assess the current level of interdisciplinary working at the Institute • Explore the interdisciplinary nature of JHI research outputs	• Online questionnaire distributed to Institute research staff • Bibliometric analysis of the authorship of Institute peer reviewed papers published in 2008-2012 as an indicator of current extent/nature of interdisciplinarity within the institute
3. Disseminate findings	
• Share results with Institute staff internally to build awareness of and interest in interdisciplinarity	• Establish a web based intranet site • Facilitated sessions and presentations with staff on both Institute sites • Regular articles in the staff newsletter • Informal communication
• Disseminate findings to external research and non-research communities to demonstrate a growing capacity/profile in understanding and enabling interdisciplinary research of socio-ecological systems • Share best practice and advance thinking (iefurther develop a community of practice) on carrying out interdisciplinary research of socio-ecological systems. • Discuss differences e.g. in understandings/attitudes found in different groups (scientists, policy makers, research funders and users)	• Peer-reviewed publications, conference presentations • International workshop • Sharing findings with key Scottish Government (RESAS) staff

2.1 Data and materials

The DICE data collection phase started in November 2012. The different strands of data collection partially overlapped (Table 2). The Hutton chief executive and science directors were interviewed after the science group and theme leader interviews were complete (without sharing this information with the executive before their interviews), and the survey questionnaire was developed in the light of interview findings conducted at the end of the data collection phase. . The literature review was ongoing for the duration of the project. The bibliometric analysis of Institute peer reviewed publications between 2008 and 2012 was carried out between late 2012 and early 2013.

Table 2: Empirical data collected in the DICE project

Data source	Time frame	Details
Survey – external	Jul 2012	• Pre-DICE survey of delegates at the Eurosoil conference in Bari, Italy • 56 responses; response rate could not be determined
Bibliometric analysis	Nov 2012-Mar 2013	• Sci2Tool used to produce co-author networks/ subject area (topical) analysis of Institute outputs between 2008-2012 based on Web of Science database
Interviews – internal	Mar-May 2013 Sep-Nov 2013	• All Science Group (5) and Theme leaders (7) • Institute Chief Executive and Directors of Science (3); 12 senior managers
Interviews – external	Jan-Aug 2013	• 6 interviews with key informants from BBSRC, SNH, SEPA, SG RESAS[2], SESYNC
Survey of Institute staff	Nov 2013	• 81 responses, of which 76 complete (response rate 20%)

The results of a bibliometric analysis of Institute peer-reviewed publications between 2008 and 2012, the analysis of a survey carried out among non-institute related scientists at a soil science conference, and the suggestions for enhancing interdisciplinary research at the Institute that we derived from the project are not included in this report but are available to Institute staff and senior management from the internal project website (http://dice.hutton.ac.uk/). The suggestions are compiled in table format identifying for each practical suggestion for supporting interdisciplinarity:

i) the expected benefits, why should this be done;
ii) the expected cost implications or any drawbacks;

[2] Scottish Government's Rural and Environment Science and Analytical Services Division. RESAS is funding a portfolio of Strategic Research from 2011-16 that aims to build a platform of knowledge that strengthens policy and contributes to the delivery of national outcomes. Two people were interviewed from RESAS as they represent a large proportion of the Institute's funding.

iii) the level at which the suggestion would need to be implemented (individual, team, institute-wide by senior management); and
iv) the source of the suggestion.

2.2 Literature review

The review was undertaken to inform the DICE analysis of IDR at the James Hutton Institute. We built on our summary of material on interdisciplinary research studied by the Institute's Interdisciplinary Reading Group (IRG) during 2011 (Morris et al., 2012). For the DICE review, we focused on literature concerning the practice rather than theory or definitions of interdisciplinary research, because the latter were predominant in the IRG material. Key areas for follow up were (i) how to do interdisciplinary/team based research that has a sound theoretical basis, and (ii) methods for evaluating interdisciplinary research.

We reviewed literature that (i) aims to help researchers take an integrative approach to research, including team science (ii) offers insights into how knowledge is produced from this approach and (iii) discusses how the processes and outcomes of interdisciplinary research are evaluated. The review was guided by a conceptual framework (see Annex 5) and based on sources identified from a rapid search by all DICE team members for relevant material on interdisciplinarity, defined as mainly literature concerning socio-ecological research, and team-based working. DICE steering group members also contributed advice and references for the review. After discussion of preliminary findings, we agreed to focus on (i) how to integrate knowledge and ways of thinking across disciplinary boundaries and (ii) how to recognise and confront differences in seeking common ground. We became aware during the review period that there is a wider range of relevant material with further insight into understanding interdisciplinarity in socio-ecological research. Areas such as system-based approaches, improvement science, and sustainability science were not included in the review but could usefully be included in any further work.

2.3 Interviews with key informants

Between March and November 2013, semi-structured interviews were carried out with 12 senior Hutton managers (seven Theme Leaders, five Science Group Leaders), the Chief Executive and the two Directors of Science, and six carefully selected external stakeholders with policy, operational and commercial backgrounds. They provided rich insights into experiences with and understandings of interdisciplinarity. They were also a source for many suggestions that could be taken forward to enhance IDR.

Interviews with the 12 senior managers were conducted between March and May 2013; the three interviews with the Executive were conducted between September and November 2013; and the six stakeholder interviews were conducted between January and August 2013.

All interviews were based around broad themes including advantages and disadvantages of interdisciplinary research; supportive conditions to interdisciplinary working; definitions and understandings of interdisciplinarity; and what indicators could be used to tell when interdisciplinary research is happening, and to assess its quality.

In addition, external interviewees were asked for their views on and attitudes to current James Hutton Institute ways of doing research. These interviews were intended to give the DICE team a flavour of stakeholders' opinions, rather than to explicitly cover the views of all stakeholders. We wanted to explore the demand for interdisciplinary research, in addition to the supply.

2.4 Survey of James Hutton Institute staff

The survey of James Hutton Institute staff was carried out in November 2013, and aimed to capture (i) staff members' understandings of what interdisciplinary research (IDR) is, (ii) to what extent they were involved in interdisciplinary research at that time, (iii) views on when it is useful, (iv) what barriers and challenges are associated with interdisciplinary (ID) working, and (v) what skills and supportive conditions are needed to work in an interdisciplinary way.

In addition to demographic and general questions, the survey included a question on attitudes to IDR (Q 7, Annex 1), which provided statements for respondents to express levels of (dis)agreement with. Some of these statements built on findings from interviews with senior managers at the Institute and elsewhere, gathered through qualitative, face-to-face interviews. While the survey was predominantly quantitative, respondents were able to provide qualitative 'free text' comments at the end of the questionnaire. Some comments received enrich and explain some of the quantitative evidence, and are reported throughout this report, and summarised in section 10.4.

Data collection

The survey was designed by members of the DICE team and a questionnaire implemented in LimeSurvey, an online survey tool. Two presentation and information sessions (one in Dundee, one in Aberdeen) were held to raise awareness of the research carried out to date and our emerging findings, as well as to launch the survey. The survey was also promoted via the Institute newsletter, and Science Group leaders were asked to forward an email to all staff inviting them to take part. The survey was open for 4 weeks in November 2013. The full questionnaire is in Annex 1.

Data analysis

Data were analysed using Microsoft Excel 2011 and R 3.0.1. Descriptive statistics have been included in the analysis as well as Fisher´s exact tests to study association between variables. The statistical significance level was set at 0.05. Due to low response frequencies, and for ease of interpretation, for each of the 19 items in Question 7 we have merged the categories 'Strongly agree/ Agree' and 'Strongly disagree/ Disagree'. The middle category of 'Neither agree nor disagree' (NAND) remains unchanged. Some 40% of respondents made free text comments in the comment box at the end of the questionnaire. These qualitative comments were grouped according to topics and summarised. Some direct quotes are used throughout this report to further ill inate selected quantitative evidence. Details of our methodology for analysing broad and narrow interdisciplinarity is in Annex 3.

Limitations

The evidence that this survey generated represents a snapshot in time. The low response rate and the unbalanced share of respondents per group mean that survey results should not be treated as representative of Institute staff or its IDR work. There may have been a bias due to self-selection of respondents, iethe sample includes those people who feel more strongly (positively or negatively) about interdisciplinary research and wanted to express their opinion. In addition, scientists move on in their work, make new connections, or change the focus of their work. The fluid nature of research makes it difficult to draw conclusions about levels of interdisciplinary research among staff or in the Institute. Figures in this report can only give estimates. If such surveys are repeated over time, we may be able to make statements

about trends more confidently. Effort to increase the response rate would increase the representativeness and confidence with which statements can be made.

The three main concerns expressed by survey respondents and our mitigation actions in those respects:

- **Possible bias towards IDR (favouring IDR)**: We acknowledge that this might have been the case in the questionnaire statements but ass e that its effect on participants' responses was minor, given that in presentations to staff and other communication the DICE team emphasised that different ways of undertaking research are valid and appropriate for different research questions.
- **Lack of anonymity of respondents**: The survey analyses did not include identifying respondents, and raw data were not accessible to anyone outside the DICE team. The way results are reported ensures anonymity of survey participants.
- **Terms such as interdisciplinary, transdisciplinary and multidisciplinary are used interchangeably and without definition**: One objective of the survey was to gather evidence about how respondents understand interdisciplinarity. The statements referred to interdisciplinarity except where involvement of non-academics was concerned. This report on the survey results doc ents the DICE team's understanding of the various terms in reference to Tress *et al*. (2004) (see annex 2) and compares responses to this definition.

3 Why practice interdisciplinary research?

Interdisciplinary research is often associated with complexity of the problems to be investigated. Such problems often involve uncertainties in scientific knowledge; h an activities and interactions; and the political, economic and cultural dimensions of knowledge affecting research and its impact. Socio-ecological systems are complex in these respects, therefore it is not surprising that interdisciplinary approaches are often called for in this area of research.

3.1 Literature review results

Aboelela *et al*. (2007) argue that interest in interdisciplinary research stems from:

- advancement of science knowledge in a wide range of disciplines and the need to link these to fully answer critical questions/facilitate application in a specific area.
- science community interest in developing new knowledge via research combining skills/perspectives of multiple disciplines.
- increasing interest in holistic perspectives, and high status interdisciplines (eg biochemistry, social psychology, informatics) .

Nissani (1997:201) lists 10 reasons why interdisciplinary research is important:

1. 'Creativity often requires interdisciplinary knowledge.
2. Immigrants often make important contributions to their new field.
3. Disciplinarians often commit errors which can be best detected by people familiar with two or more disciplines.
4. Some worthwhile topics of research fall in the interstices among the traditional disciplines.
5. Many intellectual, social, and practical problems require interdisciplinary approaches.
6. Interdisciplinary knowledge and research serve to remind us of the unity-of-knowledge ideal.
7. Interdisciplinarians enjoy greater flexibility in their research.
8. More so than narrow disciplinarians, interdisciplinarians often treat themselves to the intellectual equivalent of traveling in new lands.
9. Interdisciplinarians may help breach communication gaps in the modern academy, thereby helping to mobilize its enormous intellectual resources in the cause of greater social rationality and justice.
10. By bridging fragmented disciplines, interdisciplinarians might play a role in the defense of academic freedom.'

3.2 Interview results

An interdisciplinary approach was viewed as having many advantages or benefits by senior managers. Primarily it was viewed as being important in answering 'big questions', for example about the environment and society. Such an approach is able to tackle more complex problems. The approach was viewed as more inclusionary; it wastes less effort than single projects; and lets a problem be better understood from a number of perspectives, which, along the process of jointly defining the research could question the validity and assumptions of other disciplines; it enriches understandings and enables researchers to see gaps that might not otherwise be seen. It might help researchers see more effectively how their research fits into the

wider picture and make their research seem more valid. Despite disadvantages relating to publishing, some interviewees felt that there was more potential to publish in interdisciplinary journals, and that such journals may have more impact or wider readership. It was also suggested that although interdisciplinary projects might cost more, they may be more cost effective; and there was a perception that despite higher costs, most funders were encouraging interdisciplinary research. An interdisciplinary approach was also seen to fit well with the ethos of the James Hutton Institute –the predominant research questions that we seek to answer are of a complex, bigger picture nature that requires an interdisciplinary approach.

The Hutton Executive recognised a need for interdisciplinary research for two reasons. Firstly, to address real world problems, and they maintained that this is "a strong signature of the work we do" e.g. water, biodiversity. Secondly, there is a strategic reason because interdisciplinarity is seen to be required in order to keep the Institute competitive and to attract funding (all three Executive interviewees identified this as an important criterion for funders). In addition, they want to promote excellence and make a name for the Institute, as well as promote policy-driven science. Generally, interdisciplinary research was seen as the direction that science is now taking, and this is linked to making greater impact.

External interviewees saw that an interdisciplinary approach was required for any research undertaken in their organisation. Most of them also stressed the relationships and cooperation that are necessary to build and maintain with stakeholders, users, or the people affected by evidence-based policy and often referred to this as 'transdisciplinarity'. For example, "it's a necessary part of our work and we simply can't ignore … we can't afford not to be interdisciplinary. Most of what we do will not work unless we are."

External interviewees reflected on their own organisational structure, and to what extent they have moved towards interdisciplinarity, but acknowledge that despite the attempt to break down the disciplinary structure (ecology, chemistry, hydrology) they haven't succeeded. They felt that this is because of need for the basic core work to be delivered also. In one case, the organisation's "whole ethos now is towards that kind of…interdisciplinarity so that we can sort all these sorts of problems", and this is based on the recognition of the complexity of harms to the environment.

A holistic and solution-focussed approach is also required to meet a commercial company's demands. "People from companies they come with a problem, now they're not interested if the solution is chemistry, or if its agronomy, or if its ecological sciences, they couldn't care less! (…) they don't even talk in disciplines, they're just talking in solutions and quite often the solutions sort of fall across the boundaries of sort of traditional academic disciplines. But from their point of view it doesn't matter, they just want to know who can help them give the right answer." Similarly, policy makers do not want to get a research response from a natural science institute or perspective and another one from an economic science perspective. They need a complete picture on which they can base policy or practice.

External interviewees raised several points about the benefits of interdisciplinary research:

- **Solving complex, wicked and/ or real world problems** (as opposed to problems in the academic world). Interdisciplinarity is necessary to solve wicked problems, ie "complex problems that probably don't have a simple solution (…) Or that may not have *a* solution, there may be a range of solutions."
- "**to deliver benefit** and most benefit comes from understanding and addressing complex problems.'

- **Making a change**. "I just felt that without joining up you would never actually get any effective change, you'd understand your little bit very well but you wouldn't make any difference to society."
- **Creative application of tools and transfer of methods**. Being able "to creatively and appropriately use the vast range of tools and methods that are available for research", and "there are advantages in terms of transfer of methods and methods of enquiry as well, thinking about you know how they do research and how society is influencing the way they do research."
- **Efficiency and resilience**. "Not only does it help you to be more efficient in resolving the issue at hand, but it creates a sort of resilience in the organisation because you are passing that…you're sharing that knowledge between lots of other people otherwise we have found in the past that the knowledge is only …possessed by one or two people."
- **Combining perspectives and skills**. "It brings a range of perspectives, a range of skills and experience, a range of different training which effectively puts more ideas into solving the problem."
- "**to further the understanding** of the environment and environmental issues (…) [and] understanding sustainability."

Interdisciplinarity is also seen as a necessity because "in a large number of conservation-based science areas I think you're working at your peril these days if you don't think about how you use stakeholders in the process (…) involving all parties in the process." Stakeholders are also referred to as users and consumers. Another interviewee agreed and said that "transdisciplinarity is something that as an organisation like ours- we regulate people and we've got … so we ought to have … we have pretty good relationships with some stakeholders, businesses and so on."

Interviewees from the policy domain "always need interdisciplinary work because it doesn't matter how small the detailed scientific work is, if it's going to impact on society it will require a change in policy (…) we're always interested in policy focused research and that has to have social and economic dimensions as well as natural science and all the disciplines."

3.3 Staff survey results

Five statements from the survey have been grouped to reflect attitudes to interdisciplinary research and respondents' perceptions of what kind of problems is usefully addressed using ID approaches. The statements (4, 7, 10, 13, 19) have only been shortened slightly. Full statements can be found in Annex 1, Question 7.

These statements asked for extents of (dis)agreement about the depth of IDR, its validity and value, the character of IDR outputs,

Of the responses for each of the questions, 59.2% disagreed with the fact that ID has less depth, 44.7% believed that it increases the validity of results, and 81.6% think that it has the potential to produce more multifaceted and diverse outputs. This shows recognition of the merits of ID research.

The majority of respondents (72.4%) agreed that any complex problem facing society today requires interdisciplinary research; there was less agreement about whether or not such an approach is also necessary for less complex environmental problems. 46.1% of respondents disagreed or disagreed strongly with the latter, which indicates that even for less complex problems, most respondents agreed that interdisciplinarity is needed.

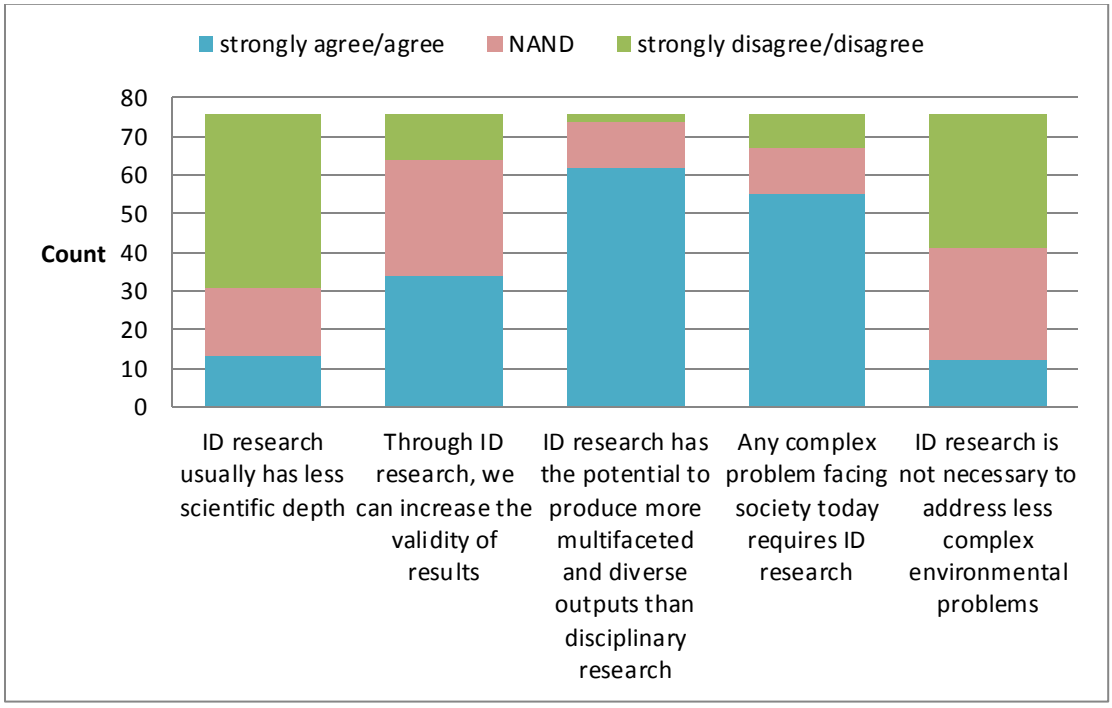

Figure 1: Responses to statements reflecting attitudes to interdisciplinary research and the type of problems it can address (n=76)

4 What is interdisciplinary research?

4.1 Literature review results

Material studied by the Institute's Interdisciplinary Reading Group (IRG) (Morris *et al.*, 2012) indicated that there is no widely agreed definition of interdisciplinary research, and that the term is sometimes used synonymously with either 'transdisciplinary' or 'multi-disciplinary' research. Repko (2012:22-25) surveyed current uses of the term interdisciplinarity and notes that it is used to describe work that:

- integrates knowledge and ways of thinking across disciplinary boundaries;
- recognizes and confronts differences in seeking common ground;
- results from a process used to study complex problems; and
- produces knowledge differently from disciplinary-based research.

There are different approaches to identifying IDR, although a core dimension is the integration of different disciplinary theory and method in research design and processes. Integrative research, as defined by Winder (2003), covers both interdisciplinary and transdisciplinary research projects. Klein (2008:119) distinguishes inter- and transdisciplinarity in several ways, but notes that 'integration is widely considered the crux of interdisciplinarity' and is also seen as the 'critical point' in evaluating transdisciplinary work.

The literature reviewed suggests that understandings of IDR range widely, from team working on research conceived and carried out using a single discipline, to research that aims to develop 'a new discourse that critically combines key elements of several disciplinary discourses yet accords with the investigator's own sense of self' (Haynes, 2002). So long as there is no agreed conception of interdisciplinary research, and no common terminology, a potential way forward may be to devise indicators that reflect the key components of IDR identified in the literature.

For example, the congruence around the idea of IDR as integrative research suggests interdisciplinarity can usefully be indicated along a spectrum of research approaches that differ by the extent of integration of disciplinary theory and method in designing and carrying out the research. Extent of integration may also be indicated by the institutional and conceptual distance between disciplines involved in the research, i.e. whether disciplines from across broad academic domains are included, and how far the research brings together disciplines with very different epistemological and methodological approaches.

Lyall *et al*. (2011) distinguish two approaches to interdisciplinary research that may help indicate IDR on such a spectrum by including the extents of academic-orientation and problem-focus of the research purpose. Both approaches aim to advance knowledge by integrating insights and methods from different disciplines; however the former is associated with discipline-based research to advance knowledge, through addressing collaboratively academic problems that cannot be solved by one discipline's methods alone. The latter is less reliant on advancing academic knowledge and is associated with the aim to bring together researchers with relevant disciplinary backgrounds to address contemporary issues that straddle disciplinary boundaries (2011:15-18).

Newing (2010) discusses interdisciplinarity in the context of training people in environmental conservation, with a focus on 'broad interdisciplinarity' (in this case, natural/social science). Her paper reviews how interdisciplinarity has been defined in the literature and sets out key approaches to a definition:

1. **Within a hierarchy of integration**: conceiving of a spectrum with less integration associated with research involving parallel use of methods from different disciplines, bringing their own perspectives to bear on a research question; and more integration associated with blending of disciplinary theory and method to construct a common framework for disciplinary efforts, and the inclusion of non-academics in the research team.
2. **By type of interaction**; from temporary collaboration on a specific problem; temporary/permanent adoption of a specific method/concept from one discipline to another; progressive convergence of both subject/method of the different disciplines involved; to the emergence of a new interdiscipline.
3. **By the extent of conceptual and institutional distance between disciplines**, ie from broad (natural/social science) to narrow (natural/natural science).
4. **By the purpose of the interdisciplinary approach**, distinguishing between conceptual (knowledge synthesis) and instrumental (addressing cross-cutting problems).

Derrick *et al.* (2011) identify interdisciplinary research as 'synthesis of data, concepts, and methods to extend the scale, scope, and range of an explanation'. But they also stress that this approach is not only about collaboration; this approach to research is 'innovative, creative, and potentially transformative' (2011:36).

Barker (2007:6) notes that Nicolescu (1997[3]) sees interdisciplinarity as being fundamentally about transferring methods from one discipline to another. He distinguishes between:

- **Application**: eg methods of nuclear physics transferred to medicine to develop new treatments for cancer.
- **Epistemology**: eg transferring methods of formal logic to general law to analyse epistemology of law.
- **New disciplines**: eg the creation of chaos theory through transferring mathematical methods to physics, resulting in mathematical physics that is applied to meteorological phenomena or stock market processes.

Haynes (2002: xiv) argues that interdisciplinary studies are based on a conception of truth that is 'situated, perspectival, and discursive', and is informed by (and informs) the investigator's own sense of 'self-authorship'. This is not to say that interdisciplinarity entails acceptance of a relativist position, in which all knowledge claims are always equal; it ass es rather that disciplines and their practitioners, activities, and concepts are already 'socially constituted'. An interdisciplinary investigator attempts to develop a new discourse that critically combines key elements of several disciplinary discourses yet accords with the investigator's own sense of self.

[3] Nicolescu, B. (1997) *The Transdisciplinary Evolution of the University Condition for Sustainable Development*, Talk at the International Congress " Universities' Responsabilities to Society ", International Association of Universities, Chulalongkorn University, Bangkok, Thailand, November 12-14, 1997, http://ciret-transdisciplinarity.org/bulletin/b12c8.php

4.2 Interview results

Among senior managers, there was a general understanding of interdisciplinarity referring to working across disciplines towards a common goal and usually to answer a 'bigger picture question', however for many interviewees that meant working between social and natural sciences, for some it may have been **multidisciplinarity** and for others **transdisciplinarity**. Despite starting the interviews with a discussion about definitions of interdisciplinarity, interviewees tended to revert back to the term they were most familiar with and what it meant during the rest of the interview. In some cases, there were slight differences in definitions used by Dundee and Aberdeen based leaders. There appear to be quite different definitions between the group and theme leaders, and there is a lack of consensus about what they mean by IDR and even to tell how it is happening. This suggests that if it is a concept the James Hutton Institute wants to promote, there needs to be greater consensus about what it actually is. It is also possible that junior staff may be less sure of what it is. A few of the leaders discussed interdisciplinarity as being transdisciplinarity which raises the question of whether the Institute might actually be aiming for transdisciplinarity. This is important because encouraging transdisciplinarity means aiming for interactions and connections to non-academics as well as with other disciplines.

The Institute Executive understood interdisciplinarity similarly to some of the senior managers as "*literally about working between disciplines, drawing the skills, knowledge from different disciplines to achieve a specific objective that cannot be achieved without…on its own with those disciplines*", and a blend between social, economic and environmental perspectives. However, their thinking moved beyond that of the senior managers in terms of "working within the boundaries of science" (i.e. making the distinction between interdisciplinarity and transdisciplinarity). One interviewee also suggested that it was a more integrated approach, framing questions from the start, and generally involving broad questions that require a diverse disciplinary input. Disciplines still need to be acknowledged: *"a truly interdisciplinary project is based around disciplinary groups working together to frame a question."* There was also an implicit assumption that interdisciplinary research is a more innovative approach which could *"create new ways of thinking"*.

There was a recognition among the Executive that *"What we need is a discourse if not a definition"*, with the suggestion that *"the principles are more important than the definition."* The main concern was that staff need to understand that interdisciplinary working is different to disciplinary work, and that it would be problematic if staff thought they were working interdisciplinarily when indeed they are not.

Among external stakeholders, there was a range of understandings. One interviewee compared transdisciplinarity with adaptive management processes, another described interdisciplinarity as "a form of consolidation of the scientific community" while yet another said "We kind of loosely are calling that public engagement, and we've got a quite big push on for the kind of citizen science and public engagement side of things because we feel it's potentially transformational in hooking to that." Interdisciplinarity has almost become a 'catch all' phrase: "at some level it's all interdisciplinary at the moment so I see it as a spectrum that goes from really quite simple things that you need to be able to come to grips with to whole full blown approaches to large scale problems." It should be noted that the same interviewee clarified that he "wouldn't describe it necessarily in terms of a structure put together to address a particular goal [but] I would see it as an environment in which people work."

When discussing interdisciplinary research, external interviewees referred to collaborative research, drawing on networks; knowledge exchange between researchers 'right from the beginning'; and jointly 'shaping the research goal'. This shows how closely their perception of interdisciplinary research is linked to communication and cooperation. One interviewee compared interdisciplinarity to "project benchmarking" and shifting resources. He referred to an example authority from the Netherlands, and was admiring that "80% of their resources are actually on problem solving projects (…). Only about 20% of evidence gathering and they've analysed their achievements in that, and they reckon that they've improved hugely their rate of achievement in their business goals." This is a curious link because both James Hutton Institute leaders and the literature recognise that there are higher costs associated with interdisciplinary research.

An interesting distinction was made by one interviewee. He believes that transdisciplinary research does not need to be interdisciplinary because "Quite often [in] ecology alone you're doing that because you may be looking for information from farmers, or landowners or crofters, as to how they manage the land."

Examples provided by interviewees for disciplinary combinations that would be classed as interdisciplinary working include:

- biochemistry and biochemical engineering;
- the interface between science and engineering;
- plant scientists and animal scientists;
- ecology and chemistry, including the operational staff, along with stakeholders, businesses, polluters, the public.

4.3 Staff survey results

More than half of the survey respondents (59%) agreed with Tress *et al.*'s (2004) definition of interdisciplinarity (Annex 2), i.e. their understanding of interdisciplinary research is closest to "research that integrates different disciplines, working towards a jointly set goal". 21% understand interdisciplinary research to include non-academic participants, which Tress *et al.* label as transdisciplinarity. For 16% of respondents, research is interdisciplinary if different disciplines work towards a number of goals under one thematic umbrella, which Tress *et al.* classify as multi-disciplinarity. No association was found between how respondents understood interdisciplinarity and which science group they belong to. See Figure 2 below.

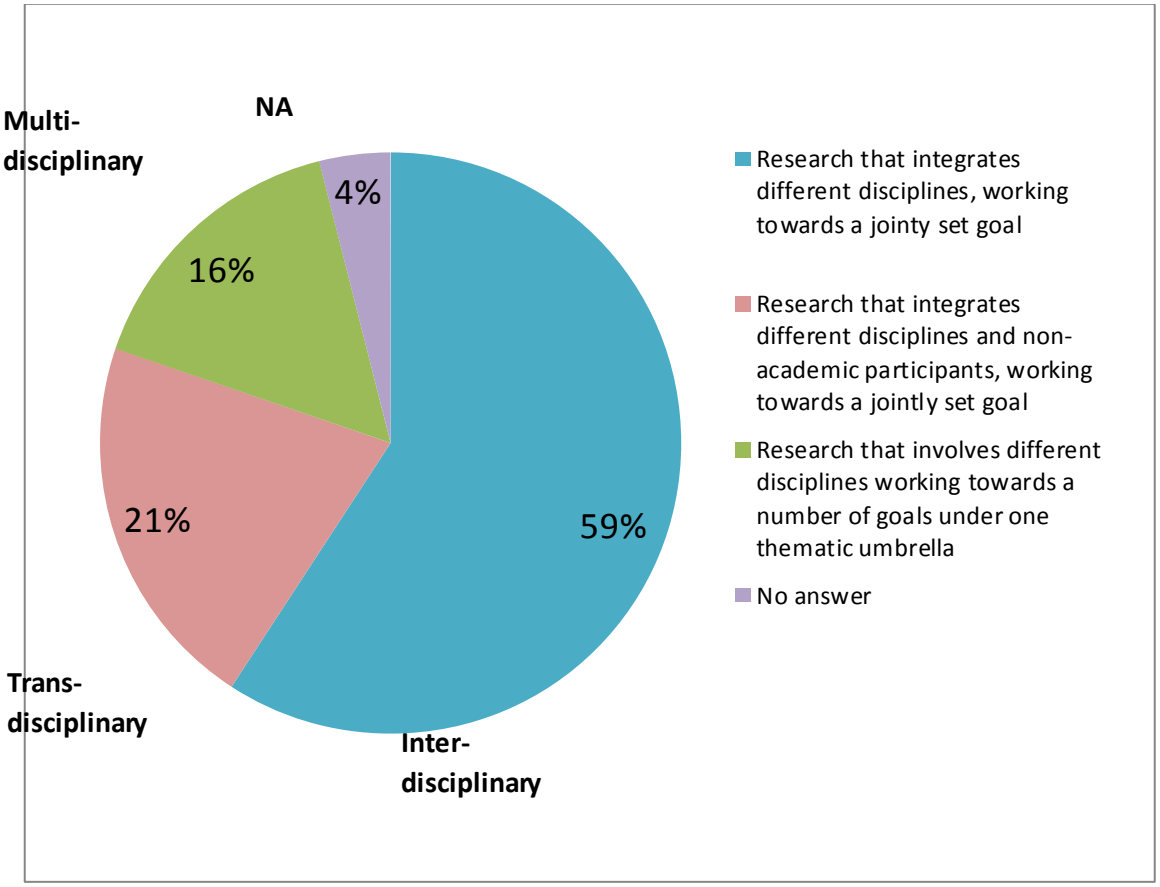

Figure 2: Which of the following statements comes closest to your understanding of interdisciplinary research? (n=76)

There was no difference between male and female respondents; both mainly selected Tress *et al.*'s interdisciplinary definition as coming closest to their own understanding of IDR (50% of the men and 68.6% of the women). Using Fisher´s exact test (p-value=0.25), an association between the two variables could not be established.

We found similar patterns for respondents who have always worked in academia, and those who have not always worked in academia (Table 3). When analysing the relationship between always working in academia and working on interdisciplinary projects, no association could be established (p=0.3, Fisher´s exact test).

Table 3: Understanding of interdisciplinary research according to academia experience (n=76)

	Interdisciplinary	Transdisciplinary	Multidisciplinary	Blank
Always in academia	22 (66.7%)	5 (15.2%)	4 (12.1%)	2 (6.1%)
Not always in academia	23 (53.5%)	11 (25.6%)	8 (18.6%)	1 (2.3%)

Of the 19 statements in the Likert scale recording attitudes towards, challenges of, and supportive conditions for interdisciplinary research, two statements (2 and 9) have been grouped to understand respondents' understanding of interdisciplinarity. 63.2% of respondents disagreed or strongly disagreed with

the statement that multi- and inter-disciplinarity mean the same thing. Surprisingly, only 3 of the 12 respondents who identified interdisciplinarity with Tress´ definition of multidisciplinarity strongly agreed or agreed with this statement. Opinions were less extreme about the need to the involve non-academics for research to be *trans*disciplinary; with 44.7% of the respondents agreeing or strongly agreeing and 30.3% of the respondents disagreeing or strongly disagreeing (see Figure 3 for actual counts). This statement does not fully map onto the definition given for transdisciplinarity in Tress *et al.*, since it stresses non-academic involvement in the research *from the beginning*.

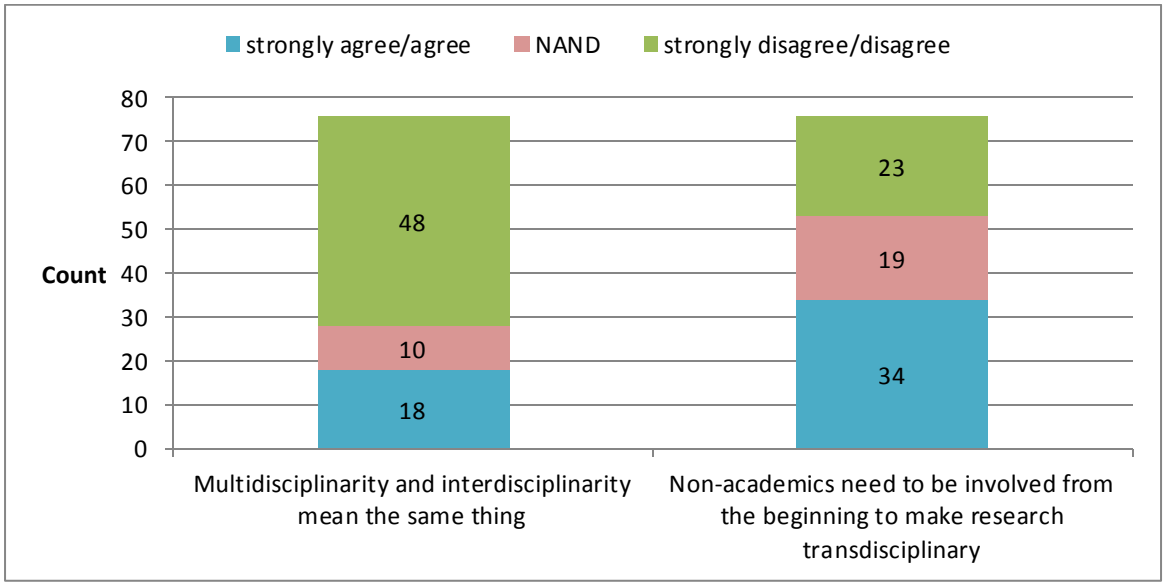

Figure 3: Agreement with two statements on the definition of interdisciplinarity (n=76)

We found evidence of an association (p=0.001) between how people defined IDR and whether they agreed with the statement "Non-academics need to be involved from the beginning to make research transdisciplinary".

Although the majority of respondents agreed with a common definition of interdisciplinarity, there was a large proportion with different understandings of what might be labelled as interdisciplinary research. This diversity in understanding was also apparent in the literature, as well as in our interviews with senior staff and external stakeholders.

5 How do we recognise interdisciplinary research?

The following section summarises the research results from a particular perspective, trying to pin down **how we could tell that interdisciplinary research is happening.** Interviewees found the question of indicators for evaluating interdisciplinary research difficult to answer. Their answers often related to definitions and benefits of interdisciplinarity, as well as the skills, attitudes and conditions that enhance interdisciplinary working. The close links between these themes is not surprising since, for example, a condition that enhances interdisciplinarity can at the same time be an indicator for its occurrence or evaluation, and how interdisciplinarity is understood will determine what would be considered in measuring its attributes.

Several survey respondents made free text comments on their understanding of interdisciplinarity. These comments illustrate the diversity of definitions of interdisciplinarity. Comments such as "all research to some extent is interdisciplinary in nature"; "collaboration between sub-disciplines may reasonably be labelled as being interdisciplinary"; and "the distinction between disciplinary and ID research is a false dichotomy" illustrate that a more nuanced definition is necessary for understanding the nature and level of interdisciplinarity at the Institute. One respondent said that "having stakeholders involved in the interdisciplinary research is also useful (…) they will be able to provide a useful, unique insight". This respondent referred to interdisciplinary research as including non-academic stakeholders, rather than using the term transdisciplinary research.

In general, external interviewees were positive about the extent of interdisciplinary work at the Institute, albeit without having any hard and fast evidence. One interviewee said about the Institute "I've always considered it [interdisciplinary research] to be one of your great strengths, I guess you'll go on to move even further that way" and that it 'compares favourably' with similar research institutes. Others, however, are unable to judge whether there should be more interdisciplinary research: "I honestly don't know if there is enough" and "I can't really comment on whether you should be even more that way."

5.1 Indicators of interdisciplinarity

Interviews with external interviewees did not reveal much information on what kind of indicators they consider useful to show evidence of or to measure interdisciplinarity. They considered interdisciplinary research to have "both scientific and user benefit" and "providing solutions to actual problems rather than parts of them." From a funding body perspective it is acknowledged that evaluating interdisciplinary research proposals is a challenge: "How do you convince a single discipline ref panel." In general terms, the bigger the problem and the project "the more likely we're (going) to need input from a variety of different disciplines."

Some interviewees found it easier to describe what they would not label as interdisciplinary. For example, if "the only thing that links them [different disciplines and work packages] is a common goal to solve the project or even worse to get the money …doesn't really consist to me of an interdisciplinary working environment." What is not interdisciplinary is when some disciplines are "not the main part of the project

but it's when you're halfway through the project…'oh it would be really useful if we could do this' and they sort of get added on at a late date, rather than being integrated from the project at the beginning."

The co-authorship of scientific publications is seen as a useful indicator by some, in particular when defining 'different' disciplines as 'natural science' and 'social science'. There was some concern that if that proportion of the Institute's output decreases it indicates a reduced level of interdisciplinarity. "[Last year] the proportion has actually gone down … now you know you asked me what (…) our aspiration was I suppose and I can't really answer. I mean I don't know whether I expect it to be 10%, 30%, 50% ... and we certainly haven't set a target because I think that would be inappropriate." This interviewee reported that 6% of all of the approximately 700 peer reviewed Hutton articles published in 2012 were co-authored by scientists from at least 2 different disciplines.

All three Executive interviewees agreed that there was no such thing as a perfect indicator to tell if interdisciplinary research was happening. Potential indicators mentioned:

- How many disciplines there were on a project report, academic article or other output.
- Attendance at seminars of researchers from different disciplinary backgrounds.
- Logic frame – maybe specific indicators which would indicate whether the big question was likely to be successfully answered.
- Number of interdisciplinary/multidisciplinary PhDs and project proposals.
- Amount of time spent discussing research problems/ideas.
- Time spent working in another disciplinary area.

They also noted that something was better than nothing, although recognised that there was potential for non-perfect indicators to be subject to manipulation.

5.2 Broad and narrow interdisciplinarity

Two of the Executives interviewed discussed the idea of a spectrum of disciplinarity, where clusters of disciplines would be represented as 'domains' e.g. natural sciences, medical sciences, and social sciences. Although interdisciplinarity is about working between disciplines, all Executive interviewees suggested that they would like staff to work more between domains and that this way of working needed to be promoted. *"It's just covering a bigger distance in terms of the distance that people have to travel in terms of their thinking and flexibility. I suppose you could…give that as a badge of honour, the more discipline distance you can travel…go across, the more interdisciplinary that's one way of looking at it I think. But it really depends on whether it's answering the question that you actually want to answer."*

In addition to asking staff directly about the extent of their involvement in interdisciplinary research, we asked them to identify disciplines involved in a recent interdisciplinary project that they had been involved in. The survey also collected information on the disciplinary background, academic qualifications and current areas of expertise of respondents. Responses were analysed according to how 'different' the disciplines are, yielding insights into broad and narrow types of interdisciplinarity (see Annex 4 for our methodology). The distinction of broad and narrow interdisciplinarity has been made previously (e.g. Klein 2008), however the categorisation used may be contested. One respondent, for example, was not able to identify the disciplines involved because they were seen as "undefinable, because it's inter- not multidisciplinary".

When the disciplines involved in a project spanned the natural and social sciences we classified this as a broad interdisciplinary project.[4] The majority (60%, n= 60) of projects identified complied with this definition. However, we argue that this definition is too limited. Additional domains or individual disciplines were stated in the survey responses, illustrating that a definition of interdisciplinarity needs to consider a wider suite of disciplines and not be confined to cross-disciplinary cooperation between social and natural scientists. Examples from the survey included philosophy, archaeology, occupational therapy, and health. If we consider a project involving information and computational sciences and/or natural/social science to also fall within the category of broad interdisciplinarity, the percentage of broad interdisciplinary projects stated by respondents increases to 78.3% (n= 60). Table 4 provides some examples of disciplines and their categorisation according to broad and narrow interdisciplinarity.

Table 4: Example disciplines from the survey and suggested classification

Narrow interdisciplinarity	Broad interdisciplinarity
• Chemistry - biology • Molecular microbiology - plant pathology • Environmental psychology - social psychology • Sociology – anthropology • Engineering – biology • Biochemistry – plant pathology • Environmental psychology – environmental economics • Hydrology – soil science • Economics - sociology	• Economics – electrical engineering • Agricultural sciences – environmental sociology • Human geography – physical geography • Agronomy - genetics • Statistics – plant pathology • Biology – bioinformatics

We can apply a similar classification to a scientist's background and expertise. If the individual has degrees or expertise in e.g. natural and/or social sciences and information and computational sciences, we can classify them as having a broad interdisciplinary background and expertise. Only 21.7% (n=60) of respondents have qualifications and expertise that fall into the category of broad interdisciplinarity.

We also investigated the change in individual's careers by comparing their disciplinary background with the interdisciplinary project they mentioned (Table 5):

- Of 60 responses (where people answered both the question on their disciplinary background and the question on a recent interdisciplinary project), 35 had training and/or expertise that we classified as narrow interdisciplinarity, and who then gave an example of a recent ID project which we classified as broad ID.
- A total of 24 responses showed no change as to the type of ID between training/ expertise and the recent project. Half (12) had broad ID training/ expertise and gave an example of a recent ID project which we classified as broad ID.
- Only one respondent reported training/ expertise in subjects that we classified as broad ID and then gave an example of a recent ID project which we classified as narrow ID.

[4] Note that number and diversity of disciplines involved in a project is an important metric but does not mean that it was interdisciplinary.

Table 5: Tracing individuals' interdisciplinary 'career': from qualifications to current projects (n=60)

Response	Number of responses	Percentage
Had narrow training but most recently worked in a broad ID project	35	58.3%
No change (12 remained broad, 12 remained narrow)	24	40.0%
Had broad training but most recently worked in a narrow ID project	1	1.7%
Total	60	100%

Essentially, we can say that most respondents came to the Institute with disciplinary training and expertise in multiple disciplines that we categorised as a narrow interdisciplinary background. A majority then moved on to work in interdisciplinary projects, most of which can be classified as examples of broad interdisciplinarity. This analysis is limited by the fact that respondents named just one self-selected example of a recent interdisciplinary project, which cannot be taken to represent all interdisciplinary projects they have worked on.

Further ideas were to use case studies or study social interactions, although it is unclear what would then indicate the level of interdisciplinarity. It was also discussed that indicators do not necessarily need to be quantitative, qualitative can also be useful. There was scepticism of the usefulness of using "social scientist on a project" as an indicator.

For indicators to be truly useful at the Institute level, they need to be able to show how principles that highlight we are moving towards interdisciplinarity are working.

5.3 Recognising interdisciplinarity

Taking the essence of respondents views on indicators, interdisciplinary research can be recognised by:

- the diverse mix of disciplines involved which leads to different perspectives being considered and integrated
- a shared understanding of the problem and jointly determined research questions
- research questions addressing complex and 'real world' problems
- effort invested into developing a common language
- on-going, preferably personal, two-way communication
- trust and good working relationships
- a tendency for tasks to take slightly longer than anticipated
- a diverse range of outputs (single discipline and interdisciplinary academic papers, synthesis papers, non-academic outputs and events), with number and background of authors playing a minor role as an indicator
- being funded by an interdisciplinary research programme
- greater advances in knowledge but possibly with less depth

In conclusion, it is difficult to measure how much interdisciplinary work happens and to assess the current level of interdisciplinarity at the James Hutton Institute. When asked to judge the share of interdisciplinary research, interviewees commonly judged by the proportion of people in a group or theme who were

working on at least one interdisciplinary project. This ranged from 50% - 100%. The lower proportions were given by leaders based at the Dundee site. It was felt that people could be encouraged to be more interdisciplinary, but that the vast majority of people working here already were involved in IDR and that research staff who came to work here did so because of the interdisciplinary nature of the Institute.

Several metrics that could be used to measure this but caution needs to be taken with overlap and fuzzy boundaries:

- By staff time (what share of their time do people spend working on interdisciplinary projects or in an interdisciplinary way),
- By number of staff (in a Science Group or affiliated with a Hutton Theme) that worked on interdisciplinary projects in the past or are currently working on such projects,
- By project (requires the classification of projects as disciplinary or interdisciplinary. Note that there are projects at different levels: someone's task could be a project in its own right, which feeds into another project),
- By funding (how much funding is tied to interdisciplinary projects).

6 How can we do interdisciplinary research better?

There is a plethora of ideas about how to put IDR into practice; we organised the material reviewed by level of focus, ie on whether it was on individual researchers (micro), teams (meso), research institutes and universities (research providers), or research funders and end users (macro). Because of these varying perspectives, it is hard to draw broad conclusions about how to do IDR better. What is easier is to identify the conditions that support IDR at each level, and these are discussed in section 7.

Much of the literature emphasises individual personality traits as equally important for IDR as disciplinary expertise, highlighting open-mindedness, tolerance of difference, and ability to work in a team as essential, with leaders of IDR teams needing a broad range of skills, particularly the ability to harness conflict within the team constructively. Research providers and funders are generally seen as key in enabling IDR, by recognising the additional investment needed for IDR success, particularly the need for time to develop the integrative approach.

There is congruence in the literature around increasing IDR effectiveness by clarifying what is expected from this approach to researching a problematic situation (at all levels); properly resourcing the transactional costs of IDR (funders and research providers); and understanding that IDR is essentially a team learning process (teams and individuals).

6.1 Research funding

Funding mechanisms were seen by senior managers as the main way in which interdisciplinary work at the James Hutton Institute is driven. It was also viewed as a carrot approach for encouraging interdisciplinarity – particularly through Institute seedcorn funding. Horizon 2020 and other EU and Research Council funding were viewed as being important interdisciplinarity drivers. Thoughts on RESAS were more mixed – some felt it encouraged interdisciplinarity, for example by pushing groups together, whilst others felt that it was not supporting interdisciplinary research enough. There was a consensus, however, that the Institute should utilise the Scottish Government funded programme to a greater extent in the next round to drive interdisciplinarity.

In their role as research funders, several external interviewees acknowledged the important influence that funding structure and provision can have. In order to increase the likelihood of receiving the evidence they need which they ass e needs to come from a number of disciplines, one interviewee said "We then saw that putting funding streams in place to enable that was going to help obviously." Another one finds that "to be a good research council we have to keep the bar a little bit ahead of what most scientists are comfortable with. In other words you have to offer opportunities as part of the package which stretches the people who are likely to be at the cutting edge of doing new things in new ways."

RESAS assess that opportunities for interdisciplinary research are 'pretty good'. The reasoning behind that is that the RESAS strategic program covers a wide range of subjects and involves many different researchers from different disciplines. "There is lots of room to manoeuvre within the various tenders to bring in more interdisciplinary work which we would welcome." In contrast, another interviewee judges that interdisciplinary research has not been written into the current round of Scottish Government funding to the

extent it could have been. He believes there is benefit in this if "it's sort of hardwired into the system whereas at the moment it is to a certain extent but not as much as it probably could."

Budgetary restrictions can impact on the extent to which interdisciplinary research is carried out. Views were expressed that resources can only be allocated to one or the other kind of research. "We've only got limited resources, it's a finite pot! (…) we need to be able to do is say 'okay we are going to put resources into project type work' which means stopping doing some stuff that we do now, which is quite difficult. But some things that we do now in a silo based operation (…) we might have to reduce that in order to be able to resource project benchmarking."

6.2 Individual traits associated positively with successful interdisciplinary research

(Micro /individual level)

Lyall and Meagher (2007:1) indicate that personality can be more important than disciplinary background, and set out a list of useful characteristics (p35) including:

- Flexibility, adaptability, creativity
- Interest in other disciplines, willingness to learn from them
- Open minded attitude towards ideas from other disciplines and experiences
- Good communication and listening skills
- Ability to bridge the gap between theory and practice
- Team working skills

Aslin and Blackstock (2010:125), reporting on findings from interviews and a workshop on using transdisciplinary approaches to the study of 'wicked problems'[5], also stress the importance of personal skills and attributes for successful use of this approach. They found that people who are 'not too set in their ways', who are willing to listen to other points of view, and who are able to resolve conflict were seen as useful members of transdisciplinary research teams.

Davies and Devlin (2007:5) note that it is difficult for academics to embody such open-minded approaches to research, given that different disciplines have their own 'mental models, cognitive maps or frameworks, or "paradigms", and that once students have been inducted into a discipline it is hard for them to 'see things any other way'. As a starting point, they recommend compiling checklists or glossaries of key terms for each discipline involved in an interdisciplinary project, yet recognise that these are no substitute for deeper understanding of the disciplines of team members (2007:7).

Lyall *et al.* (2011:29) note that interdisciplinary researchers need a high level of tolerance for ambiguity, as well as the patience to spend time exploring the problem at hand. Repko (2012:58-63) lists some 15 traits and skills common to interdisciplinary researchers. As well as those already noted, he mentions enterprise; love of learning; reflection; appreciation of diversity; and humility. Naiman (1999:292) found that although the literature shows general agreement that '*successful interdisciplinary research demands good science as much as it demands personal values related to patience, trust, responsibility, and honesty*', this is matched by agreement that putting these attributes into practice is very difficult.

[5] Problems that are fundamentally complex, broad and systemic (Aslin and Blackstock, 2010:118).

Inclusion of researchers with strong disciplinary backgrounds is also widely agreed to be important when building interdisciplinary teams. Morse *et al.* (2007) present three main conclusions from their experience of running an interdisciplinary program under the NSF IGERT[6]:

- Input from disciplines is crucial to interdisciplinary work, and researchers need to be able to link their disciplines to the team effort;
- Clarity about degrees of integration in each interdisciplinary research project is needed- the level of integration should be based on problem definition and pragmatism; and
- Proactive planning and ongoing reflection are needed to ensure required levels of team integration are in place.

Pennington (2008:7) in her approach to interdisciplinary research as a learning problem identifies three processes that are important for individuals- cognition (the way we process information), creativity (the cognition that generates original information that is appropriate in the context), and motivation ('the initiation, direction, intensity and persistence of h an behaviour'). Each of these processes interacts with one another and also with social processes and the normative environment (iethe values held) and are therefore difficult mechanisms to understand.

Cunliffe (2007:19) recommends taking a 'virtue approach' to interdisciplinary teaching and learning. He argues (2007:23) that the urgent current social, economic, ecological and cultural problems cannot be solved by single disciplines, nor by any interdisciplinary approach to education because the key issue is 'what to do with all our "know how" and "know that"'. His response is that we must 'generate the necessary ethics for responsibly knowing' and argues therefore that wisdom, and its corollary generative wisdom (citing Solomon *et al.*, 2005[7]), needs to be understood 'as normative for an interdisciplinary approach to educational practice'.

A virtue approach entails giving priority to 'cultivating character traits' for promoting 'wise or responsible' ethical actions and judgments; beliefs and knowledge; and creative practices. Cunliffe (2007:23) argues that 'virtue thought' 'has the capacity to be the hub to the interdisciplinary spokes of the educational wheel' because it is based on ' practical wisdom' that 'emerges from deep structured character traits aimed at discerning ethical, epistemic and creative actions and beliefs'.

He refers (2007:20) to MacIntyre's[8] concept of a community of practice, a coherent social structure of standards and expectations, where membership entails commitment to these standards 'through practising the virtues of justice, courage, and truthfulness'. The virtue approach to interdisciplinary teaching and learning recognizes that such communities of practice, with shared expectations, can be deliberately cultivated, monitored and maintained to promote character traits for ethics, knowledge, and creativity.

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[6] National Science Foundation Integrative Graduate Education and Research Traineeship, http://www.nsf.gov/pubs/2011/nsf11533/nsf11533.htm Aims to produce graduate students 'with the interdisciplinary backgrounds, deep knowledge in chosen disciplines, and technical, professional and personal skills to become in their own careers the leaders and creative agents for change' (NSF, 2006)

[7] Solomon, J. L., Marshall, P. and Gardner, H. (2005) Crossing boundaries to generative wisdom. In R. J. Sternberg and J. Jordan (eds) A handbook of wisdom: psychological perspectives. Cambridge: Cambridge University Press, pp. 272-296.

[8] Macintyre, A. (1981) *After virtue*. London: Duckworth.

Chettiparalamb (2007:29) refers to Anbar (1973[9]), who conceives of a "bridge scientist, an interdisciplinary team member whose focus is on paradigmatic rather than terminological conflict". Anbar identifies four types of people who become bridge scientists, who have varying levels of ability:

- Professionals who are strongly grounded in a particular discipline and, having satisfaction in terms of scientific curiosity and recognition by their peers, have become adventurers (most active and creative);
- Professionals who are strongly grounded in a particular discipline and might like to stay in it, but who feel forced to get involved in other disciplines because their own discipline is becoming obsolete and non-marketable (less enthusiastic);
- People who had some rather superficial training in one or more disciplines, who now find that they can get work and consequent recognition as generalists (more suited to marketing rather than project generation or management); and
- People who have moved into managerial, sales or other essentially bridge positions, but have not been prepared to fulfil a bridge role (and who may become "the most serious obstacles" in interdisciplinary research).

As already indicated in some of the earlier interviewee statements, communication and work in interdisciplinary teams is much easier if people are willing to get involved in interdisciplinary research, which "depends a lot on the mindset of the people (…) and to a certain extent it's down to personality." Others described it as an "attitude and mind that is open to that kind of thing." Interviewees acknowledged that a mindset is not easily changed. Often the specialists are very good in their discipline but less willing to broaden their scope which might come at the expense of the time they have available to further their expertise. "We have some people like that, and it's difficult to shift those into that [interdisciplinary] sort of behaviour." "But you do get a few people who are in their own little silos that it's so small and narrow, they might be very, very good at that but they're very reluctant to step outside of it and meet people halfway!"

Interviewees felt that this kind of mindset is more typical in older people. They also see that self-confidence can play a role in someone being willing to work interdisciplinarily which is compared to 'stepping out of one's comfort zone'. Very young researchers would also lack that confidence so it is the "group in the middle who have been here a few years, they've built up some confidence, they've worked in a range of different projects, yeah they're great [at doing interdisciplinary research]." Scientists with "a broad outlook on life" and "people who are politically aware with a small 'p' (…) are more likely to be adjusted to interdisciplinarity." Another interviewees said that people would need to be open and "have their blinkers off sometimes and perhaps [be] prepared to compromise."

Attributes that are conducive to interdisciplinary working are described as follows: people "who are very outward facing, very much into trying to think of solutions that are out of the box if you like and very much like to talk to other people and work in teams and learn all the time, so learning, being really sensitive to that, receiving things, receiving information which is not necessarily in their own very focused discipline."

[9] Anbar, M. (1973) The "Bridge Scientist" and his Role, *Research/Development*. July, 30-34.

Another aspect raised was that of personality profiles. "Scientists tend to have aptitudes which suit them to being scientists in the first place. They like detail, they like order and structure, they tend to be quite introverted (…) [and] that sits uneasily with creativity, risk, big picture considerations and so on (…) in some ways there is a lot of benefit in bringing the less familiar kinds of personality types that come from the artistic and the creative end and also tend to be quite good at the management end of it into groups of scientists in order to challenge the way they think." Another interviewee had studied the personality types of scientists, which sit along a spectrum of cosmopolitan – local orientation and a basic – applied orientation.

People who are good at interdisciplinary research "tend to be good communicators, and they want to do interdisciplinary research, they see a value in other disciplines." Senior managers expressed that to be effective in a team and an interdisciplinary environment, people needed to be open-minded and receptive, should value and be interested in other disciplines, and have good interpersonal skills. Both senior managers and the Executive mentioned that people on a team need to like, or at least respect and listen to each other. Despite these characteristics being associated with increased interdisciplinarity, senior managers suggested that there are still places for more specialised, highly-focused individuals in interdisciplinary teams who may not have some of the positively identified personality attributes. There was a perception that people can be persuaded to work in interdisciplinary teams if they can see the benefits for themselves.

6.3 Importance of team working and strategies for success

(Meso: group/team level)

Fundamentally, the literature claims that team working requires:

- Input from disciplines, and researcher ability to link their disciplines to the team effort
- Clarity about degrees of integration in each interdisciplinary research project, with the level of integration based on problem definition and pragmatism
- Proactive planning and ongoing reflection to ensure required levels of team integration are in place
- Good leadership, with leaders having three key skill sets (i) cognitive (including clear vision of the project's aims and objectives); (ii) structural (eg gaining support and facilitating linkages); and (iii) processual (ensuring productive interactions) (Lyall *et al.*, 2011).

Team working also depends on developing a common language; effective knowledge exchange; and trust among members.

Morse *et al.* (2007) highlight the importance of team working in interdisciplinary research, and note that there can be tension between breadth/depth of team members' knowledge. They indicate that it is extremely useful to have team members with prior experience of this research approach. They recommend that interdisciplinary research teams adopt a 'focal theme' as the overarching umbrella for the research. This is also recommended by Davies and Devlin (2007:5) who see 'idea dominance' as a central feature for interdisciplinary research, and argue that a 'key idea needs to be mutually agreed upon as being important by all concerned'. In adopting such a key idea, team members need to be able to distinguish dominant ideas from weaker ideas and between ideas from specific disciplines and ideas that are interdisciplinary in nature (2007:6).

An overarching or focal theme for an interdisciplinary research design is an important communication device, which links the different research components to the team vision (Morse *et al.* (2007:7). Identifying the focal theme helps frame complex research by highlighting issues related to the problem, the analysis, and the research audience, and assisting in increasing integration (Morse *et al.*., 2007:9). Derounian (2007:26) describes the inherently interdisciplinary area of community development as having an overarching theme of 'place', and other interdisciplinary areas of academic study have also been developed around key themes, eg social policy and welfare, media studies and communication.

A current example of an overarching theme is the International Association of Hydrological Sciences (IAHS), which is using the theme of 'Panta Rhei—Everything Flows' in dedicating its research activities over the next decade (2013-2022) to interdisciplinary study of change in hydrology and society (Montanari *et al.*, 2013:1). In this approach, hydrological systems are the interface between the environment and h an needs for water. The aim is to develop an improved interpretation of the water cycle by connecting changing dynamics to rapidly changing human systems. This approach is seen as the way to improve the ability to predict water resources dynamics, and foster sustainable societal development in a changing environment.

Davies and Devlin (2007:5) argue that disciplinary language, or vocabularies, and their relationships to epistemology also raise challenges for interdisciplinarity, especially when the same words are used in different ways in different disciplines. Morse *et al.* (2007) recognise this as an issue for interdisciplinary research teams, and emphasise that there is a need for common language in interdisciplinary teams, because of different meanings for the same words from different disciplines, and use of terms unknown to other disciplines, as well as a need to understand the different disciplinary paradigms/epistemological stances that are involved.

Sánchez-Colberg (2007:42) argues that identifying key words shared across disciplines can be used as the basis for developing a common 'language'. In her example of integrating dance and architecture, she identifies such keywords as structure, dynamics, space, effort, weight, time, flow, density, volume, projection and design. All are familiar to architecture students, and for dance students are the building blocks of Laban's[10] theories of movement and space. In her example, she shows that the challenge of working interdisciplinarily is not based on issues of 'language', nor on the 'conceptual' body of knowledge, but centred around 'the nature of the body-as-tool' with dance and architecture students having differing experiences and views of the 'body-knowledge-subject'.

Aslin and Blackstock (2010:126) also found that some areas of research, eg GIS and computer-based modelling were seen as 'inherently integrative', and able to incorporate other people's agendas. This is further explored by Kragt *et al.* (2013:322), who note that modellers' broad perspective on environmental systems gives them an overarching perspective that makes them well-placed to lead and facilitate integrative research processes. Burd (2007:15) places interdisciplinarity at 'the heart of the subject domain of Information and Computer Sciences (ICS)'. Students studying within the ICS discipline must learn to work with experts from other disciplines and become skilled in learning new domains for application of ICS expertise.

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[10] Laban, R. (1975). *Laban's Principles of Dance and Movement Notation*. 2nd edition edited and annotated by R. Lange. London: MacDonald and Evans. (First published 1956)

Morse *et al.* (2007:10-12) provide a set of recommendations for interdisciplinary team efforts:

- adopting an accountability strategy that provides clarity about deadlines, requirements and responsibilities;
- implementing a communication strategy that allows formal meetings to discuss progress/mutual learning;
- thoughtful and strategic selection of team members that have the necessary qualities-vision/dedication/problem-solving;
- clarity about temporal/spatial scales for all team members' work;
- recognition of and respect for timings needed to complete aspects of the research, eg data gathering seasons/breeding cycles that constrain timing of research;
- identification of focal theme(s) as overarching guide for the work;
- allowing of time to develop the approach to the problem at hand;
- interdisciplinary training that is targeted to the project at hand, eg seminars on both interdisciplinary working and disciplines involved; and
- identifying mentors to focus on team integration issues to provide oversight of team working and help resolve any conflicts arising.

Naiman (1999:293) notes the complexity of problems tackled by interdisciplinary research, concluding that resolving these issues needs a research team that is drawn from a wide range of knowledge bases (including people from beyond traditional academic settings), and ideally has experience of working together. He identifies features that are characteristic of interdisciplinary approaches and that need to be recognised and addressed:

- time needed (12 months or more) to familiarise team members with each other's methods/terminology;
- time, effort, and costs needed to finalise project design are higher than for single disciplinary work;
- different levels of commitment among team members and reliance on strong leadership of research;
- longer than usual period needed for publishing results;
- need to incorporate social and political insights into research design;
- time lost for developing team members' expertise in their own discipline; and
- perception of interdisciplinary scientists as 'less competent or accomplished' and interdisciplinary research as 'less exacting'.

Pennington (2008:9) stresses the social nature of interdisciplinary research, regardless of the scale of the project. She argues that successful collaboration entails 'orchestrating the environment and interactions' of the team to ensure effective knowledge exchange among team members that result in innovative approaches to the problem at hand. She acknowledges that group learning can be difficult, and echoes other authors on the amounts of time and commitment needed. Knowledge exchange among team members needs to provide the sense of a subject rather than detailed understanding. To underpin team learning, Pennington translates Maslow's hierarchy of needs[11] (motivational factors) to the factors that are incurred by participation in collaboration (from lowest level (1) to highest level (5) needs:

[11] Maslow, A.H. (1943). A theory of human motivation. Psychological Review, 50(4), 370–96.

Maslow's factors	Collaborative factors
1. Physiological needs (food, water, sex, sleep)	1. Physical mechanisms (physical presence, links between participants)
2. Safety needs (security, protection, predictability)	2. Group intactness and trust (connectedness of team members, application of individual expertise, innovative assessment of participant contributions)
3. Love needs (friendship, family, belonging)	3. Social relationships among team members (accommodating differences, constructing shared meanings)
4. Self-esteem needs (confidence, achievement, respect of self and others)	4. Sense of individual strengths and perspectives (valuing disciplinary perspectives, allowing coherence to emerge, maintaining the field of inquiry)
5. Self-actualization needs (fulfilment of potential, ultimate desires)	5. Team actualization (shared vision, goal congruence, convergent thinking from each part of the work)

Trust among team members is commonly seen as a factor in successful team working, and is particularly important when people from different disciplines are collaborating. Aslin and Blackstock (2010:126) found that trust and reciprocity are important for team working, as is shared views of research ethics that are process-based. They also found that participation in a 'real project' was a key element in the process of learning about how to work transdisciplinarily, with effective project management ensuring that all team members feel empowered. Pennington (2008) also notes that interdisciplinary researchers need to be able to apply the information they learn from knowledge exchange during collaborations to engender new conceptual links.

Lyall *et al.* (2011:3) note that while trust among team members is important in any collaborative project, in interdisciplinary research it is 'crucial'. In building trust, they emphasise the need to deal with any conflict arising in team discussions rather than gloss over them. They stress that disagreement should be acknowledged as an expected issue, particularly in the early stages of project development. They suggest that face-to-face interactions can help avoid ongoing conflict, and that 'creating an open environment characterised by mutual respect helps achieve trust (p59). Lyall (2008:4) suggests that it is important to agree the project publication/authorship credit strategy at an early stage, and this also assists in creating trust.

Developing interdisciplinary teams is very much an organic process. This process takes a lot more time because people who are coming together in a team need to build up levels of trust, exchange knowledge and increase understanding of each other's' disciplinary backgrounds and ideas. It also links to the theme of attending informal events, in order for such relationships to develop and being able to meet other people, and time spent on this should be viewed as very important and a priority in order for interdisciplinarity to develop. The time aspect was also acknowledged by the Hutton Executive, in terms of staff needing time to overcome barriers of an interdisciplinary approach, such as different disciplinary languages. Establishing a different culture can take time, which the Executive believed could be facilitated through the Institute values.

Communication plays an important role in interdisciplinary research, in particular in building effective teams of (inter)disciplinary researchers. External interviewees stressed that communication and exchange is particularly important in interdisciplinary research because it brings together people with different working cultures and training. Therefore building understanding and a common language is needed for an

interdisciplinary team to work successfully. Communication can be supported in a number of ways. Two external interviewees stressed the important role of the project manager, in particular in interdisciplinary projects:

> *… the importance of the project manager, the importance of a person whose job it is to make sure that everybody knows what they're supposed to do and that people's understanding where it's lacking can be identified and addressed is about the only way you can make these things work. (…) [It needs] that kind of skill (…) understanding how to make groups of people function effectively together.*
>
> *… to bring in project management almost as an additional discipline in its own right so that you've not got a group of half a dozen scientists all coming from (…) their own discipline, having somebody who sort of sits above them and brings them altogether and delivers a project (…) managers should be appointed who want to manage, know how to manage, realise that they're going to take a reduction in scientific input, … and they're provided with suitable training.*

A similar role was described for an IDR facilitator "having an understanding of what the problem is and what the potential solutions are and then assembling all the different bits uh…regardless of academic boundaries." Such a facilitator is tasked with understanding individual scientists' backgrounds, "where they're coming from and what are the important things of their discipline", and then to "find some common ground and common language to move forward (…) to break those barriers down." 'Facilitating' could be part of the job of a project manager. This notion was shared by senior managers, who saw good leaders as important for driving teams. Such a leader needed to be a 'big ideas person', and a mentor who could nurture early career researchers.

Opportunities for informal communication were viewed by senior managers as conducive to interdisciplinarity, in terms of 'getting people together,' and building relationships. It is important that people get to know each other and feel more comfortable around each other – so they are more likely to be relaxed and open in more formal settings. However, it was stressed that meeting and mixing cannot be forced. Although often more formal, seminars were also viewed as important. Presenting and participation encourages early career researchers, makes people aware of each other's research, and 'gets people mixing and talking'. A practical suggestion from an external interviewee was to hold weekly short seminars given by an Institute scientist on their work, pitched at a general level with a 15-20 minute presentation, and opportunities for short questions, taking at maximum half an hour. "You're not taking too much out of your time and building sort of institutional awareness."

6.4 Team leadership

The literature on interdisciplinary research emphasises the role of the team leader as being particularly important in this type of work. Lyall *et al.* (2011:72) provide a list of the qualities needed to be a good interdisciplinary team leader.

In addition to the characteristics needed for interdisciplinary researchers, they also include tact, assertiveness, perseverance, proactivity, and ability to ensure openness as well as progress

with the work. Lyall *et al.* (2011:72) also note Gray's[12] three categories of responsibilities for interdisciplinary team leaders- cognitive (including clear vision of the project's aims and objectives); structural (eg gaining support and facilitating linkages); and processual (ensuring productive interactions).

Lyall *et al.* (2007:1) stress the importance of both personal attributes and leadership for interdisciplinary researchers: 'In many ways, personality can be a more significant factor than discipline base'; noting that '[w]e have, for example, found that successful interdisciplinary teams are led by people who themselves have a strong interdisciplinary background' and exhibit the following traits:[13]

- Interest in a wide range of subjects;
- Respect for other disciplines;
- Willingness to promote the success of other disciplines;
- Good interpersonal and team-building skills; and
- Proactive in engaging with other partners.

While Lyall *et al.* (2007:2) recognise these traits are useful for all research, they see them as 'absolutely essential' for interdisciplinary research.

Newing (2010) notes that some of the biggest barriers to interdisciplinary research are about achieving team agreement about framing research questions, collecting and analysing data, and the validity, ambiguity, and relevance of results. To assist team leaders in these tasks, Pennington (2008) draws on social science research on boundaries to advocate the inclusion of 'boundary spanners' in an interdisciplinary research team. Boundary spanners with networking ability, who are also entrepreneurs, innovators, cultural brokers, trust builders and catalytic leaders, need to be viewed by the team as a legitimate member with recognized skills in negotiating between fields, even though their role in the research may be limited or peripheral.

Lyall (2008:3) provides advice for interdisciplinary research team leaders on effective group working mechanisms, arguing that the most successful projects entail 'a lively process of interaction in order to explore commonalities and differences and establish relationships between disciplinary partners'. Planning should include more time for conceptualizing the research problem and research scheduling than for a single disciplinary collaboration. Team leaders should also schedule high levels of group working, recognising that this needs to be facilitated, which is particularly important in the framing parts of the work.

Lyall (2008:3) suggests a short checklist for distributing team responsibilities:

- identify and assign expertise appropriately (not everyone has to be involved in all tasks);
- keep an open mind about new methods;
- consider how to structure analyses so that different types of findings, from different disciplines' methods and data, can be integrated;
- recognise that team responsibilities may go beyond standard/traditional areas of expertise; and
- identify the role and contribution of research users/ other stakeholders in the team.

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[12] Gray, B (2008) Enhancing Transdisciplinary Research through Collaborative Leadership, American Journal of Preventive Medicine, 35/2(Supplement 1, August), s124-32

[13] Bruce A., Lyall C., Tait J. and Williams, R. (2004) "Interdisciplinary Integration in the Fifth Framework Programme", Futures, 36/4, 457-470.

She also sets out strategies to foster communication within the team:

- frequent face-to-face meetings/networking events;
- regular video-conferencing when team members are located in different institutions;
- joint fieldwork;
- social events;
- applying rewards and incentives to teams rather than individuals;
- considering using existing techniques and computational tools for integrating data; and
- writing together to encourage integration across disciplines. (p3)

Sommer (2000:4) concludes that for interdisciplinary team leaders, 'the challenge is to retain the flexibility and focus possible in a field of study in bringing together people from a wide variety of backgrounds while allowing individual members to maintain identification with the disciplines and professions in which they were trained'. Bammer (2013b) identifies 'harnessing difference' as the essence of collaboration, and a team leader needs to be able to recognise when differences can be harnesses to progress the research, or managed if they are obstructing the research. Bammer (2013b) identifies six types of differences that need to be taken into account: personality, mental models, epistemologies, cultural norms, team role skills, and emotional intelligence.

For Bammer (2008), '*the point of working with someone else is that they have different perspectives, skills, resources or other attributes that contribute something relevant to addressing the research problem, either in improving understanding about it or in implementing that understanding in decisions and action*'. She notes that little attention has been given to the practical issues of interdisciplinary research, and highlights three activities critical to successful research collaboration (2008:1):

- effectively harnessing differences;
- setting defensible boundaries; and
- gaining legitimate authorization.

Differences vary, and range from personal attributes, incentives required, conceptualisations of research, and working style, to other attributes all potentially creating unproductive conflict. Bammer (2008:2) recognizes that disagreements and competition can provide a vital stimulus to creativity, and recommends minimizing rather than eliminating the tensions and disputes that prevent people from working together constructively. She recommends two strategies to harness difference: fostering reciprocity; and making transparent the personality differences of the team to build trust. In a later paper, Bammer (2013b), notes that methods exist for covering differences in personality; cultural norms; mental models; emotional intelligence; team role skills; and epistemologies (but gives no references), and recommends dialogue methods (McDonald *et al.*, 2009[14]).

Bammer also notes that deciding which perspectives to include in interdisciplinary research projects can be difficult because of external restraints (eg funding); lack of knowledge about disciplinary relevance; and, on occasion, political pressure and power imbalances between disciplines and practice areas, or between individuals. She recommends (2008:3) using one of two strategies to set research boundaries, scoping, and

[14] McDonald, D., Bammer, G., Deane P. (2009) Research Integration Using Dialogue Methods, ANU E-Press; http://epress.anu.edu.au/dialogue_methods_citation

critical system heuristics. Her own scoping questions (quoted from Bammer, 2006) help identify research dimension and set priorities:

Dimension

What is known about the problem?
What can different interest groups and academic disciplines contribute to addressing this problem?
What areas are contentious?
What are the big picture issues? In other words, what are the political, social and cultural aspects of the problem?

Priorities

Why is this problem on the agenda now?
What support and resources are likely to be available for tackling the problem?
What parts of the problem are already well covered and where are the areas of greatest need?
Where can the most strategic interventions be made?

Bammer (2008:4) recommends Ulrich's Critical System Heuristics (2005[15]) as another helpful set of questions that can be assist thinking about collaborative research boundaries:

1. Motivation for the collaboration;
2. Sources of power in the collaboration;
3. Sources of knowledge for the collaboration; and
4. Sources of legitimation for the collaboration.

In her approach to interdisciplinary research as a learning problem, Pennington (2008) identifies three processes that are important for individuals- cognition (the way we process information), creativity (the cognition that generates original information that is appropriate in the context), and motivation ('the initiation, direction, intensity and persistence of h an behaviour'). Each of these processes interacts with one another, and also with social processes and the normative environment (ie the values held) and are therefore difficult mechanisms to understand. Pennington uses both Maslow's famous 1943 hierarchy of needs (see page 38, above) and constructivism as frameworks to provide better understanding of these individual processes in collaborative learning.

At the wider population level, the political, economic, and cultural context influences support for interdisciplinary research and the impact it can make on complex areas of science and policy. Derrick *et al.* (2011) note that where institutions are 'financially strapped' they tend to focus on core activities, so that disciplinary research takes precedence. They also note that government support for interdisciplinary research fluctuates according to political and policy changes (2011:33).

6.5 Physical Spaces

In addition to mental spaces for interdisciplinary work, physical spaces were identified as important by interviewees. Most Hutton interviewees mentioned the role that suitable buildings and office layouts have in

[15] Ulrich W (2005). A brief introduction to critical systems heuristics (CSH). ECOSENSUS project web site, Open University, Milton Keynes, UK, 14 October 2005.
http://kmi.open.ac.uk/projects/ecosensus/publications/ulrich_csh_intro.pdf

encouraging interdisciplinarity. The Aberdeen site was viewed as more conducive to interdisciplinary working compared to the Dundee site due to staff in Dundee being housed in many separate buildings. One of the external interviewees had carried out a study with staff at the Dundee site previously, which found that physical distance of staff is a barrier to interdisciplinary working. Study participants said the physical layout of the Institute hindered good communication. The structure of the two sites reduces chances of informal exchange happening. "For example some of my best conversations are with people I've just happened to b p into in the canteen … or going around the site and sort of not a planned meeting."

It is important to have informal spaces where people can gather informally to chat. The dual-site setup makes it difficult to build relationships between staff from different groups and disciplines; the SEGS group and staff in Dundee were given as an example. There were different ideas about getting different disciplines to mix within buildings, but the need to share ideas with people of the same discipline was also mentioned. Being grouped together in groups was seen to enhance career development and disciplinarityy, while a mixed setup may promote interdisciplinarity. The Hutton Executive highlighted the physical infrastructure – groups sharing a single coffee room, and informal places for people to meet – as important areas of interaction.

One external interviewee voiced suggestions similar to those from Theme and Science Group Leader interviews. For example, the issue of "too many people working in portacabins who have no real incentive to leave their portacabin very often" should be addressed, and provisions made for informal exchanges to happen: break out rooms, corridors, "water fountains at the end of the corridor, coffee machines, whatever, where people would naturally sort of b p into each other and have the ability to first of all just to get to know each other and secondly have those sort of informal discussions that can lead to the great ideas."

Another external interviewee reported on their organisation's experience of closing two facilities and moving all staff into one new building so that people from different disciplines are co-located in the same building. They face a constraint in that laboratories need to be locally present (linked to organisation's remit/mandate) so the extent to which staff can be co-located is limited. The idea of 'critical mass' came up several times, in that it only makes sense to follow the interdisciplinary path if you have sufficient staff numbers so there is a group around every discipline/expertise (also in order to guarantee training and cutting edge research). Otherwise it is preferable to team up with other organisations and get the missing expertise from them.

6.6 Education for interdisciplinary research

Increasing interest in interdisciplinary research in academic scholarship is evident from the changing nature of the academy since the 1940s (Klein, 2004), which historically had tended towards increasing separation of disciplinary study. Some interdisciplinary areas of study are now well-recognised, for example biochemistry in the natural sciences, and social policy in the social sciences. More recently, there have been increases in interdisciplinary subjects being researched and taught, for example conservation biology and natural resource management.

While the Scottish Curriculum (7-14) and the American Association for the Advancement of Science guidance on primary and secondary education both refer to interdisciplinary learning, higher education institutes are widely seen to have a key role in education for interdisciplinary research. Writing about training

requirements for students of environmental conservation, Newing (2010) notes the focus on broad interdisciplinarity, involving both natural and social science in this field. However, she also notes that interdisciplinarity often refers to the inclusion in curricula of any social science content; vocational skills training; integrative or practice-based exercises, sometimes with no indication of disciplinary content; and the (variously defined) 'h an dimensions' of conservation.

Newing (2010) argues that interdisciplinarity has to be academically focused in each contributing discipline, with understanding of disciplinary differences, especially in epistemological theory and scientific tradition. She concludes that the minim content in natural or social science-based conservation undergraduate programmes should include:

1. An introduction to other (natural/social) science perspectives on environment;
2. Basic training in the other (natural/social) science methods, research design and theory;
3. Some vocational skills training where possible; and
4. Integrative problem solving tasks that can be used in teaching any/all of the above three.

Klein (2004) writing about transdisciplinarity[16] states that 'education is vital to future prospects', and that interdisciplinary studies are key in building capacity for collaborative work across disciplines. Klein argues that transdisciplinary education is needed at all levels of schooling, from primary to higher education (2004a:522), as well as being 'incorporated into professional practice' (p523). She further argues that adding new transdisciplinary courses to existing disciplinary studies is not the answer, but rather that transdisciplinarity needs to be understood as '"basic" education' (p523).

Bentley (2007:12) addresses the problem in interdisciplinary education of using other disciplines to open students' minds to new ways of thinking about their discipline without such exposure leading to 'deconstruction of their emerging discipline identity'. She recommends exposure to other disciplines' teachers as a key element in disciplinary education for undergraduate students, emphasizing that at root, disciplines are no more than discourses. She refers to Bakhtin's theory of dialogism, ie what happens when discourses encounter each other. He suggests that while dialogue may be superficially 'friendly or hostile, convergent or divergent', underlying this 'there is always a struggle for influence'. While speakers listen carefully to each other, they do so 'to inform and reinforce their own discursive position'. The outcome is "dialogized heteroglossia" (Bakhtin, 2001:1199[17]), defined as the "co-existence of socio-ideological contradictions between the present and past […] between tendencies, schools, circles and so forth" (2001:1213).

Bentley (2007:12) recommends using a type of 'dialogic encounter', when a speaker from a second discipline engages actively in literal dialogue in a disciplinary classroom about their disciplinary perspective on a theme under study. The intellectual integrity of staff, their understanding of the students' discipline, and their skill

[16] For Klein, 'transdisciplinarity' is 'transcultural, transnational, and encompasses ethics, spirituality, and creativity. It is not a new discipline or super discipline'. (2004a:516) For her the key difference between interdisciplinarity and transdisciplinarity is that transdisciplinarity questions disciplinary thinking 'through the principle of articulation between different forms of knowledge' although transdisciplinary research is 'based on disciplinary practice' (2004a:524).

[17] Bakhtin, M. (2001) Discourse in the novel. In V. Leitch (ed.) The Norton anthology of theory and criticism. London: Norton, pp. 1190-1220

in dialogic encounter should counter the tendency towards heteroglossia, but given the linguistic dynamic of dialogue, this tendency needs to be recognised and explicitly acknowledged.

Bringing source material, the speaker explains how their discipline interprets them, shares their valuing of their own epistemologies, and familiarises the students with another specialist disciplinary language. Bentley (2007:13) argues that this approach gives the second discipline 'a more powerful and persuasive voice', and makes an interdisciplinary encounter 'more open-ended, untidy and exciting'.

Morrow (2007:34) argues that interdisciplinary teaching and learning is potentially best employed in developing courses that cut across disciplinary boundaries. This approach can fill the gaps between disciplines, and also maximise connections between them, making it appealing to those who recognise the value of a more holistic worldview. She notes that the trend towards modular teaching in universities may also promote interdisciplinary learning, because this allows students (notionally at least) to access courses in other disciplines during their degree. Morrow (2007:36) warns that for vocational areas of study, eg law, the demands of professional accreditation can lead to 'course cramming' , an approach that does not value innovative and imaginative cross-disciplinary teaching and learning.

Penlington (2007:39) argues that students on interdisciplinary courses receive mixed messages about assessment, threshold, benchmark and output standards that may reduce their confidence in their learning. To address this issue he recommends ensuring 'equity within assessment' and that assessment methods must be equally suited to all students, regardless of their dominant disciplinary area.

Burd (2007:16) recommends using a problem-based learning approach. She notes that academic staff are concerned about dilution of core teaching by introducing interdisciplinary elements in undergraduate courses, and that students often resist the demands of interdisciplinary learning. She suggests (2007:16) that clear communication and the appropriate focusing of learning outcomes can address these barriers. Staff can be shown how core skills are being taught via case studies using diverse topics, which also increases variety and interest. Making clearer the key skills that interdisciplinary learning provides, and how these skills are to be assessed, can address students' concerns.

Derounian (2007:26) also characterises interdisciplinary education as a learning process that encourages people collectively to improve their skills, confidence, awareness and understanding, thus developing resources and influence. In the context of undergraduate community development education, he recommends (2007:29) that teaching and learning is based on Kolb's Cycle [18], which emphasises concrete experience (visiting and hearing from others); self-reflection leading to an output; and experimentation in assembling and presenting the output. He also notes that this approach is compatible with a social constructivist approach to learning, ie sharing experiences and discussing ways forward.

Evely *et al.* (2012:2) emphasize the importance of understanding the processes and mechanisms that facilitate learning and knowledge exchange at different governance scales, and how processes of communicating resilience research can be integrated with mechanisms that promote greater depth of learning. They point to lack of appreciation of how knowledge is perceived and constructed, which affects

[18] Kolb, D.A. (1984): Experiential learning: experience as the source of learning and development, Englewood Cliffs, NJ: Prentice Hall, http://academic.regis.edu/ed205/Kolb.pdf

both implementation and outcomes of knowledge exchange processes. This, in turn, has implications for the co-generation, acceptance and use of knowledge, and ultimately, how complex social-ecological problems are approached and managed (2012:3).

Evely *et al.* (2012:14) provide an overview of a spectrum of conceptualizations of knowledge and their links to knowledge exchange. They conclude (2012:18) that as yet there is no single model of knowledge or knowledge exchange to ensure that research outcomes are used by intended audiences. They argue that understanding the alternative approaches and their epistemological bases, however, makes for better planning of future knowledge exchange processes for better fit to the context in which they operate.

Incentives for interdisciplinary working can be integrated into the way in which career evaluations are carried out, and they can be materialised in the way early career researchers are encouraged to work interdisciplinarily. Senior managers were of the opinion that staff (particularly early career researchers) need to develop both disciplinary and interdisciplinary expertise. Disciplinary expertise is easier to value in career evaluations. Potentially there is a need to consider how to value interdisciplinary outputs (which may be more difficult to produce) more effectively at the James Hutton Institute whilst still allowing staff to have the potential to have a successful career outwith the Institute. It was also noted that the PPDR process[19] is more about individuals rather than team development. The views of the Executive were that interdisciplinary research can be promoted through demonstrating the progress you can make and the benefits of being involved in such projects. They also stressed that people need to be aware of what interdisciplinary working is and what its advantages are.

There were suggestions that it may be more difficult for early career researchers to get involved in doing interdisciplinary research because they still needed to develop an expertise in their disciplinary area. Becoming an expert in an area was seen as being important in being able to contribute to an interdisciplinary team, and also enabled individuals to have confidence in their research and being able to critique or respond to the ideas of different team members. Early career researchers were viewed as needing more support to develop interdisciplinary projects or needed to be 'nurtured' into or given exposure to interdisciplinarity. There was a perception that early career researchers should be included in interdisciplinary projects so that they could 'get a flavour' of the benefits of working in an interdisciplinary way. The dominant way to get established in a discipline was viewed as being published in disciplinary journals. There was recognition that getting published in interdisciplinary journals was important too, but it may be more difficult, associated with a lower impact factor, and with issues around the order of co-authors. The Executive recognised a need to strategically favour interdisciplinary PhDs, and make seedcorn funding available for interdisciplinary projects.

Generally, interdisciplinary research is not something that young researchers are trained in at university; they need to learn this approach 'on the job'. Post-docs and young investigators working on projects are seen to be more open minded and enthusiastic. Giving these people incentives to talk to one another across the traditional boundaries supports interdisciplinary exchange because they are already open to other views and approaches. Interviewees stressed that what "is self-evident really is you can't make everybody change. You simply make the people who want to change, you reward them for it, you particularly try to make sure

[19] Personal Performance Development Review, the Institute's annual appraisal system.

the exemplars of what they've done are well discussed and all the rest of it. You create an environment which favours it."

But training in interdisciplinarity is not only about enabling scientists from different disciplines to come together. "For early or mid-career scientists I think it's really important that they have…its almost giving them training, making sure that they're aware of the bigger arena that they're working in (…) it is really important that you try to make sure that people do know of and are aware of the government perspective on a whole range of things" such as policy documents. Another set of skills that an interdisciplinary – and even more so a transdisciplinary – researcher needs is the ability to translate research for various target audiences, in order to "give the research impact."

A poignant practical suggestion was made be an external interviewee: "Probably the first stage in terms of training is just raising awareness of what other people in the Institute are doing."

7 What do supportive conditions for interdisciplinary research look like?

A number of themes emerged from our research relating to nurturing interdisciplinarity through supportive conditions such as: time – it takes longer to do interdisciplinary research; team building – team members need to be open-minded and receptive; the matrix system and management – conceptually the matrix system is good but themes should be more fluid; spaces – good work environments can enable interdisciplinary working practices; careers – interdisciplinarity should be considered in career evaluations and early career researchers need to develop their own discipline; funders – are the drivers of interdisciplinary research, most were viewed to be good at this but opinions about RESAS were more mixed; informal chats/seminars – were seen as a good way of getting people to communicate informally.

Understanding how to nurture interdisciplinarity is important in an institute that aims to develop a culture of interdisciplinarity. Supportive conditions mentioned that already exist or can be developed to enhance an interdisciplinary way of working include team building; sufficient time and good two-way communication; personal attributes and mindsets; culture and working environment; physical spaces; incentives for staff, training and skills; and research funding. These supportive conditions were recognised by internal and external interviewees alike.

7.1 Institutional support for interdisciplinary research

(Macro: institutional/wider population level)

Much of the literature on interdisciplinary research argues that institutional support is essential. Lyall (2008:2) notes that interdisciplinary research tends not to fit the traditional discipline-based academic structures within universities. Existing systems of funding and rewards are often not applicable to academics undertaking interdisciplinary work. Grigg *et al.* (2003:1) note that although cross-disciplinary research is seen within the research funding and higher education environment as an increasingly mainstream activity, and receives much support in principle, difficulties remain in supporting such activity in practice.

Academic institutes

Nissani (1997:203) sees the rewards of interdisciplinary research in three (overlapping) categories: increases in knowledge; other social benefits; and personal benefits. He identifies academic emphasis on discipline-based institutional arrangements as the main barrier to interdisciplinary research, in that this approach is less useful for academic careers due to less research funding and fewer publishing opportunities, and reduced potential to achieve seniority. His conclusion is that the academy needs to foster interdisciplinary research alongside discipline-based research, recognising the need for generalists and specialists to deal with diversity and interconnections in the real world. (1997:214).

Morse *et al.* (2007:10) identify three key roles for higher educational institute support for interdisciplinary research:

- experienced institutional mentors to support interdisciplinary researchers/teams;
- funding for training needed to ensure team members to fully participate in interdisciplinary work; and

- project funding that takes account of the fact that interdisciplinary work takes longer.

Aslin and Blackstock (2010:126) found that researchers working on interdisciplinary projects see value in involving senior management in this type of research, ensuring internal support for this approach. Derrick *et al.* (2011:33) suggest that existing institutional funding can be used to support interdisciplinary research at low cost, via self-sustaining collaborative networks across disciplines or departments.

Funding agencies

Lyall *et al.* (2013:62) state that support from funders is crucial for realising the benefits of interdisciplinary research, especially from large-scale projects. This is because funders make the decisions that impact significantly on resources available for this type of research, how it is shaped, including the extent of integration involved, and also its effectiveness (p67).

Key roles for funders include:

- stimulating interdisciplinary research initiatives (by identifying issues that are best addressed using this approach);
- establishing the 'architecture' of an interdisciplinary programme (by selection of leader/locus/funding routes/methods of accountability via evaluation processes); and
- providing the additional training or infrastructure needed to ensure interdisciplinary research capacity.

Derrick *et al.* (2011:33) suggest that the risks involved in interdisciplinary research mean that public funding is not as well-suited to this research approach as private sector funding. However, they recommend that public/private funding should be targeted towards individuals who are likely to build successful interdisciplinary research teams, allowing them to pursue, over time, this approach to research.

Policy makers

Chettiparamb (2007:1) states that within UK policy circles, interdisciplinarity has been normatively accepted, leading to the drive for interdisciplinarity in both teaching and research being encouraged through the Higher Education Academy and the Research Councils.

Tress *et al.* (2004:22) include a set of expectations from inter- and trans- disciplinarity research from a German policy maker perspective. For them, this type of research should be:

- useful for policy;
- politically relevant (ie contributes to policy aims);
- theoretically robust;
- providing results that solve problems and that can be applied to different fields of practice;
- carried out in co-operation with end users;
- increasing the esteem of scientific community for these research approaches that focus on normative areas, eg sustainability, including recognition that this approach does not produce results that are not scientific; and
- increasing capability of researchers to work in this way, ie of those willing to extend their mental school of thought from their original discipline.

Morse *et al.* (2007) present three main conclusions from their experience of running an interdisciplinary program under the NSF IGERT[20]:

- input from disciplines is crucial to interdisciplinary work, and researchers need to be able to link their disciplines to the team effort;
- clarity about degrees of integration in each interdisciplinary research project is needed, the level of integration should be based on problem definition and pragmatism; and
- proactive planning and ongoing reflection is needed to ensure required levels of team integration are in place.

7.2 Interview results

The interviews examined the supportive conditions that can be developed or already existed in order to enhance an interdisciplinary way of working at the Institute. Many points were mentioned by senior managers from the Institute and the external interviewees alike, although they sometimes used different terms. There is recognition that interdisciplinarity needs supportive conditions in terms of:

- team-building, time and two-way communication;
- personal attributes and mindset of people;
- culture and working environment;
- physical spaces;
- incentives for staff, training, and skills;
- research funding.

People are at the core of shaping the working environment in an organisation. Comments on this point were made by external interviewees. There are various ways to enhance an interdisciplinary culture or working environment in a research institute. Management or the organisation needs to adopt clear incentives for interdisciplinary work. An external interviewee was convinced that "The message that's coming from senior management is important that….whether that sort of activity is encouraged or discouraged." Bringing scientists from different disciplines together just for the sake of it is unlikely to work. Instead, one interviewee suggests "the way I see that works best is when you have a problem that needs addressing and you bring people together rather than bringing people together first and then looking at well what could we do together? (…) There's more of a pull rather than a push, I don't think you can push sort of interdisciplinary working it has to be a pull."

External interviewees acknowledged that "a culture and a behavioural change in our own staff" is needed for interdisciplinarity to thrive. "There's something about comfort zones and familiarity in culture and all of that which is quite important in (…) engendering an interdisciplinary environment." The aim should be to create an environment, an atmosphere, where people feel confident they can share ideas without being criticised in a way that would adversely affect perceptions of them. People need to feel comfortable to speak up, ask questions and critique other people's ideas and approaches, and not be afraid of being "criticised by people who do not have the same depth of understanding, because if you can't do that then you can't let the

[20] National Science Foundation Integrative Graduate Education and Research Traineeship, http://www.nsf.gov/pubs/2011/nsf11533/nsf11533.htm Aims to produce graduate students 'with the interdisciplinary backgrounds, deep knowledge in chosen disciplines, and technical, professional and personal skills to become in their own careers the leaders and creative agents for change' (NSF, 2006)

sociologist, or control engineer into your space at all." Otherwise, "they won't share their ideas until they're really developed for fear that someone will say you don't really know what you're doing!" A practical suggestion was giving a seminar on a project proposal before it is submitted.

One interviewee with more extensive insights into the James Hutton Institute structures and procedures commented on the appraisal system. It should not be entirely driven by academic performance but have a mechanism in place that allows interdisciplinary work to be recognised and promoted. "Otherwise people will say well why should I do that? (…) 'my appraisal last year I was told I had to publish another 3 papers. If I want to get promoted that's what I've got to do that's going to be my prime focus. I'm not going to go up to Aberdeen and talk to a group of social scientists about something that may or may not lead to research in the future, (…) it's not going to progress my career." Meeting expectations and targets set is determined by the (limited) time available to do work. If staff are very busy fulfilling their (disciplinary) projects, they don't want to take the time to talk informally to colleagues or attend seminars that are not directly relevant to their work. This reduces chances for communication and exchange that was recognised as important earlier.

Another point raised was about inter-staff competition. "Probably the thing that works best in terms of engendering a real interdisciplinary outlook is to try to find a way of minimising the sense of competition within the Institute, within the grouping or the institution." How precisely this could be achieved was not detailed.

The James Hutton Institute operates a matrix management system where staff are grouped into one of five Science Groups, but their research belongs to one or several of seven Research Themes. The matrix structure was viewed very positively by science group and theme leaders. The Executive was convinced that the matrix breaks down disciplinary barriers. There was recognition among senior managers that staff need to fully understand the matrix and be able to contribute across themes. Generally, the concept of themes was seen as good, and there were suggestions that the themes should be more fluid but still be able to pull people into a common area of research. Themes needed to be revisited at times and should be organic rather than contrived. The Executive recognised that thematic rather than group placement would be more difficult as themes are more fluid than groups at the Institute. They also saw the Theme leaders as the guardians and instigators of interdisciplinarity at the Institute, a view which was mirrored in a comment from an external "The theme leaders can do a lot within their theme of bringing people together."

Most senior managers perceived that the Executive is supportive of the concept of interdisciplinarity. There was a perception that in order to increase levels of interdisciplinary working, it needed to be the ethos of all the staff and not just senior management, ie it needed buy-in from all staff. The Aberdeen site was viewed particularly positively and the predecessor Institute was said to have had an interdisciplinary culture dating back from at least 1990s.

7.3 Staff survey results

There was strong support among survey respondents that good interpersonal communication (a result of good communication skills), a common language, and a shared understanding of the problem are prerequisites for productive interdisciplinary research (Figure 6; full statements 1, 5, 6, 8, 12, 16, 17 and 18 in Annex 1, Question 7). There was no disagreement with the statement that disciplinary experts are needed in ID teams, and 73.7% agreed that experience in different working environments is beneficial for an

individual's capacity for ID research. (56.6% of respondents have also worked outside academia.) A similar level of agreement (72.4%) was evident for the benefit of informal interactions, such as in the canteen.

The only gender difference we could find about attitudes to the role of communication was in response to statement 7 "Anybody can do interdisciplinary research regardless of their communication skills". Here, a greater percentage of women (74.3%) than that of men (39.5%) strongly disagreed or disagreed with this statement. On all other statements relating to communication (1, 5 and 16), there was no difference between males and female respondents.

In the comments provided by some respondents, there was an emphasis on communication as an important aspect of interdisciplinary research, but not the most important one: "Interdisciplinary collaboration requires more than anything the willingness to develop a shared understanding, this is much more relying on willingness to step out of the disciplinary comfort zone than communication skills although the latter do help they do NOT guarantee success and true interdisciplinarity." The point on open-mindedness was picked up by several other respondents, e.g. "A more open, supportive and unassuming stance is more conducive to interdisciplinary research." There was also a recognition that "If someone is in their silo and doesn't want to come out they won't."

In addition to the supportive conditions and skills expressed in the survey statements, respondents recognised others such as "Support from line-managers and group leaders is essential to facilitate individuals to undertake interdisciplinary research" and "there is so much pressure to be a specialist that time devoted to crossing the boundaries will probably be seen as a barrier."

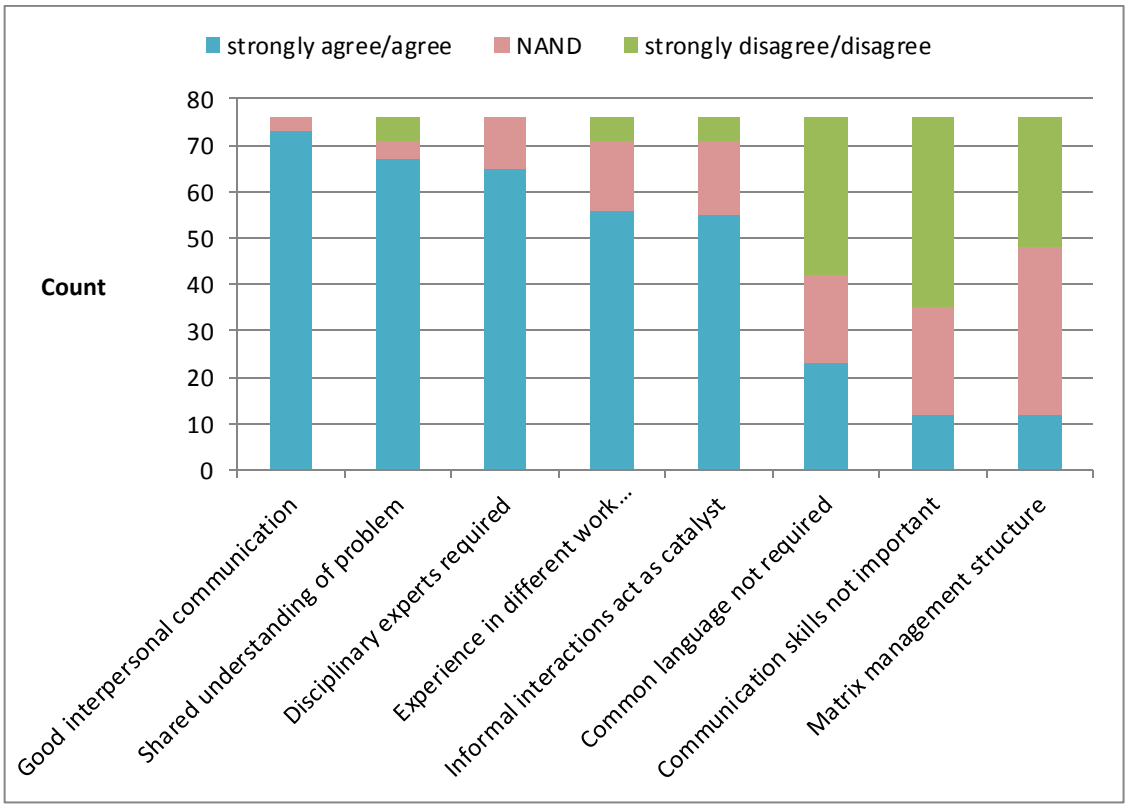

Figure 6: Responses regarding supportive conditions and skills for interdisciplinary research (n=76)

Interestingly, 47.4% of respondents were not sure whether the matrix management structure supports interdisciplinary research, and 36.8% disagreed with the statement. This uncertainty is in contrast to the dominantly positive view of the matrix structure by theme and science group leaders and the senior executive. One respondent commented "Matrix management has the potential to encourage MD but as an institute we rarely 'mix up' the disciplines." Note how MD (multidisciplinarity) is used even though 18 statements out of 19 used the term 'interdisciplinary' (and one 'transdisciplinarity') and most of the questions in the survey focussed on interdisciplinarity.

Other comments were critical of the matrix structure, but in relation to management more generally: "I do not believe that the matrix structure facilitates interdisciplinary collaboration. This is in large part due to the fact that management in general is not effective enough." Senior management were criticised for having "eroded the fine interdisciplinary traditions of both institutes through their mangled attempts at matrix management." There was evidence in the comments that the matrix structure is unclear to some staff.

In addition to what the survey captured in quantitative terms, respondents commented on the following aspects of what ID research needs:

- conscious decision that the ID approach is appropriate in each case;
- researchers with
    - personalities suited to this approach;
    - appreciation and understanding of different disciplines involved;
    - prior experience of working across disciplines and with non-academics;
    - diverse backgrounds, allowing for 'creative friction' within ID teams; and
    - ability to recognise others' competences and their own limitations;
- strong disciplinary foundations as a basis
- good leadership (including understanding of all disciplines involved);
- more development of theory and method to be robust;
- support and encouragement from management (including new ways of measuring individual/collective success, and allowing time for links to be made);
- latitude to evolve through willingness to take part rather than be imposed;
- patience regarding publishing opportunities, recognising that these will increase (and impact increase) as ID research becomes more accepted by quality journals.

Several suggestions were made about how the Institute could support ID research. One comment stressed that ID needs "an organisation with an appropriate time culture that recognises the uncertainty involved in this approach". One suggestion for activities to support 'mixing' of staff was to hold annual cross theme and group meetings. PhD students were seen to potentially be able to play a larger role: "Why not let PhD students discover how their work might be related to overall JHI visions and how it can be strengthened by interdisciplinary relations?"

- Overall, "it is important to create a 'presence' for interdisciplinary research in the institute". Interdisciplinary research needs to be valued more, and incentives established to (also) work with 'people down the corridor' as well as outside the Institute. This respondent also highlighted the need to change the fact that it is still seen as better to be first institute author on a paper than the twentieth, and that credit for winning funds tends to go to a single individual.

- One comment highlighted the difficulty of 'getting it right' in developing disciplinary experts at the same time as good interdisciplinary researchers: a more disciplinary arrangement of the core research scientists is more conducive to the former; and while the current structure of interdisciplinary themes, and indeed interdisciplinary groups, benefits the latter, it also separates people with similar skills, thus reducing the opportunities for discussion and learning within disciplines.

8 How should we evaluate interdisciplinary research?

The literature about evaluating interdisciplinary research is still developing. End point evaluation is the most common form, and this has tended to measure outputs, at the expense of understanding the practices and processes of interdisciplinary research.

The literature indicates that evaluation should be part of the research design, and should involve IDR teams from the outset. Focusing on ongoing evaluation by research teams themselves allows for social learning (also described as collective or collaborative learning) as the research is carried out, and for adjusting of processes that are found to need improving.

Such a focus may also lead to discussions of knowledge exchange within the team if communication is seen as less than optimal. Different sets of criteria are needed for (i) review of interdisciplinary research proposals, and (ii) for evaluation (formative and summative) of the research. A lack of accepted indicators to assess interdisciplinary research quality means that the academic value of such research is questioned.

Klein's 2008 review of evaluation of interdisciplinary and transdisciplinary research found that evaluation is 'one of the least-understood aspects' (2008:116). She argues that there cannot be a single, universally applicable method for inter- and transdisciplinary research evaluation because of its context-specific and multidimensional nature (2008:123). She also notes that 'readiness' to undertake trans- and interdisciplinary research depends on 'antecedent conditions that are flexible enough to allow multiple pathways of integration and collaboration'. Such readiness includes the construction of 'epistemic communities' and the production of 'new cultures of evidence' (2008:117).

8.1 Approaches to evaluation of interdisciplinary research

Klein argues that the complexity of interdisciplinary research, which is 'grounded in the philosophy of constructivism' needs more than traditional approaches to evaluation; that 'appropriate evaluation is made, not given' (2008:122). She sets out seven generic principles, derived from the literature, which can usefully frame thinking about evaluation across the differing contexts of both inter- and disciplinary research approaches (2008:118-121):

1. **Variability of goals**, ie sensitivity to context and flexibility, recognising that criteria and indicators of quality will vary depending on the goals of the research.
2. **Variability of criteria and indicators**, ie recognising that conventional metrics of evaluation tend to be disciplinary-based, and that criteria that address experimental rigour, aesthetic quality, fit of framework and data, and power to investigate unsolved disciplinary questions are better suited to inter- and transdisciplinary research evaluation.
3. **Leveraging of integration**, ie viewing integration as the essence of these research approaches, assessing the quality of the process of linking intellectual integration and collaboration, including assessment of antecedent conditions such as opportunities for communication, structural support, and a transdisciplinary ethic.
4. **Interaction of social and cognitive factors in collaboration**, ie recognition that these research approaches involve a social process of knowledge production, with evaluation defined as

5. 'collaborative and discursive learning process' and communication and participation during the research process as key aspects of evaluation.
6. **Management and coaching**, ie assessment of organizational structures, leadership, and the nurturing of integration during the research process.
7. **Iteration and transparency in a comprehensive system**, ie recognition that iteration is key for collaboration and that non-linear evaluation models are needed to capture relationships between research outcomes and research impact.
8. **Effectiveness and impact**, ie returning to principles 1 and 2 on variability, recognising that interdisciplinary research impacts are 'often diffused, delayed in time, and dispersed across diverse areas of study and patterns of citation practice' (quoting Boix-Mansilla, 2006[21]), and that many long term impacts are not predictable.

Lyall *et al.* (2013: 63) note that evaluation on completion of research programmes has tended to measure outputs, at the expense of understanding the practices and processes of interdisciplinary research. End point evaluation also means that there are no means to improve effectiveness and integration during the course of the research.

They argue that 'evaluation of interdisciplinary research urgently needs to be tailored more appropriately' (2013:68), and cite a number of authors who indicate that the lack of accepted indicators to assess interdisciplinary research quality means that the academic value of such research is questioned. Lyall *et al.* argue that criteria are needed both for review of interdisciplinary research proposals, and for evaluation (formative and summative) of the research. Meagher (2012) used a case study approach to evaluate four large-scale, longer term UK Research Council-funded research programmes costing between £18m and £34.5m. Five key factors were identified for success of interdisciplinary research programmes:

1. Identification of the appropriate locus (or loci) of interdisciplinarity, and which level(s) should form the main platform, eg programme or sub-programme level, based on the bodies of knowledge underpinning the research.
2. Consideration of how to achieve integration and coherence of the research, both at the beginning of the work and by including activities (supported by funders) to promote these throughout the research period.
3. Selection of project leaders who are able to inspire team members in this unconventional way of working, and good use of external advisers.
4. Pro-active management of the research to ensure that networks and capacity are built, with funders recognising the need for this and supporting this style of management.
5. Development of knowledge and increasing the skills, competences, and abilities of researchers to work in an interdisciplinary way to promote capacity in this approach, with funders taking steps to ensure that learning from interdisciplinary experiences becomes part of collective organisational memories.

Box 1 gives more information about this evaluation, which is particularly interesting in its blending of knowledge exchange and interdisciplinarity evaluation, and ensuing recommendations.

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[21] Boix-Mansilla V. Assessing expert interdisciplinary work at the frontier: an empirical exploration. Research Evaluation 2006;15:17–29.

Box 1: Institutional evaluations of interdisciplinary research

(Macro: institutional/ wider population level)

Dr. Laura R. Meagher, Technology Development Group (2012) Report Rural Economy and Land Use Programme (Relu) Societal and Economic Impact Evaluation (REFERENCE PS110020) ESRC, http://www.relu.ac.uk/news/Evaluation.htm

'Approach and Methods

Exploring Relu as an imaginative experiment to facilitate interdisciplinarity and knowledge exchange that can fuel evidence-based policy and practice, this evaluation was grounded in a conceptual model which considers research impact to be a function of the interaction between the content of the research, the context for its application and the processes of user engagement. We have made use of the ESRC's Conceptual Framework for Impact Evaluation (ESRC 2011) and our own flows of knowledge conceptual model (Meagher *et al.* 2008). We captured multiple types of impacts, as seen from not only researcher but also stakeholder perspectives.'

'Recommendations

1. Continue to collaborate across funding bodies to support interdisciplinary research initiatives with a strong theme of Knowledge Exchange and development of integrated solutions for complex problems. Take deliberate steps to ensure "organisational learning" and retention of lessons learned, to the benefit of funders and, perhaps via mentoring, individuals establishing initiatives in the future.' (execs)

8.2 Measuring collaboration

Mâsse *et al.* (2008) identify collaborative processes as a key process in team science, and their paper provides tools to measure these processes, particularly in cross-disciplinary research. They rely on Rosenfield's 1992[22] conception of transdisciplinarity collaboration as developing 'shared conceptual frameworks that not only integrate but also transcend the individual disciplinary perspectives represented by various members of the research team' (2008:152).

Mâsse *et al.* used their early stage evaluation of the US National Cancer Institute's Transdisciplinary Tobacco Use Research Centers to create and validate methods and metrics to assess collaboration and integration within the centers, and to develop and assess a conceptual logic model that links the phases, processes and outcomes of large team science initiatives. The logic model has five general 'clusters': collaboration; communication; professional validation; scientific integration; and health impacts (2008:152).

A researcher survey to assess collaboration and integration was completed by 216 of the 234 eligible center researchers. The survey used 23 items (all including 5-point, Likert-type response formats) to assess collaboration. These items had three broad factors: satisfaction with collaboration; impact of collaboration; and trust and respect in the collaborative context (2008:153). The survey also included a further 15 items (all including 5-point, Likert-type response formats) to measure attitudes towards transdisciplinary research (2008:154).

[22] Rosenfield, P.L. (1992) The potential of transdisciplinary research for sustaining and extending linkages between the health and social sciences. Soc Sci Med: 25:1343-57

Results showed that higher levels of satisfaction with collaboration were associated with positive views of disciplinary integration and perceptions of institutional progress in new methods, science, models and interventions. While Mâsse *et al.* validated their methods of measurement, they stress that linking these measures to more tangible outcomes requires longitudinal research over one or more decades (2008:159).

8.3 Assessing how well interdisciplinary research is conceived and carried out

Derrick *et al*. (2011[23]) note that the key measure of interdisciplinary research is 'whether it solves the problems it set out to solve', but set out Ed Hackett's four factors to measure whether the research is well-conceived and carried out (2011:36):

1. Intellectual, social, and technological capital;
2. Diversity in person and agreement on process;
3. Intensity and focus (including emotional energy); and
4. Duration (of intensity).

Metrics recommended by Derrick *et al*. for institutional evaluation of interdisciplinary policy are (2011:37):

- How many collaborators does a person have?
- What are their fields?
- What fraction of a person's publications is collaborative?
- How many new collaborations have been established over the past five years?

They also place much importance on interim goals and periodic review to ensure research progress (2011:34).

Bammer (2008:5) sees the benefits for research from research teams 'thinking more systematically about research collaborations' as extending to evaluation. She relates the key activities of interdisciplinary research – harnessing differences, setting defensible boundaries and gaining legitimate authorization – to evaluation of research design, methods, results, and conclusions. Suggested evaluation questions include:

- **Research design**: How defensible are the boundaries of the collaboration? Were all the necessary actors and considerations included? Were limitations dealt with effectively? Was the normative base sound?
- **Methods**: Were effective integrative methods used? Would other methods have made useful contributions? Were incidental differences managed effectively or did they get in the way of producing successful outcomes? Were the collaborators treated fairly in terms of meeting their interests in the collaboration and in the distribution of the rewards of the collaboration?
- **Results**: How well did the collaboration meet its aims? Was effective integration achieved? Were influential new insights produced? Did effective action result?
- **Conclusions**: Can the claims made by the researchers be substantiated? Has research independence been compromised?

[23] Guidance produced from the results of the workshop "Science on FIRE: Facilitating Interdisciplinary Research and Education," held March 28-29, 2011, hosted by the American Association for the Advancement of Science and the Colorado Initiative in Molecular Biology of the University of Colorado, Boulder.

8.4 Evaluation and learning by team members during and after the research process

Meso (group/team level)

Importance is also attached to reflection of the process by team members while the project is ongoing, and the learning experience derived from the collaboration. Pennington *et al.* (2008) use a collective learning strategy model from the field of organizational learning, but recommend that a model for science collaborations still needs to be developed. Strategies are available from the field of organizational learning, but because of the difference between business and research environments, Pennington (2008) recommends development of methods specifically for science collaborations.

Evaluation may often be carried out by people outwith the research team, but the literature also recommends some form of evaluation by the team, and this includes reflection on their work both during the work and after completion, and on the learning experience derived from the collaboration.

Pennington (2008) recommends Argyris and Shon's (1996[24]) double-loop learning model for collaborations across disciplines as a collective learning strategy. The model has two strands: the first involves developing the action strategy for the group, which can then be evaluated during the research; the second involves developing the collective thinking strategy, ie the methods that the group uses to determine their collaborative action, based on their shared vision. Pennington emphasises that this initial vision is dynamic, because of the nature of the research. The vision needs to be allowed to evolve on the basis of regular and ongoing evaluation as the research progresses, to take account of emerging (unanticipated) changes in the definition of the problem.

Pennington also stresses the need for focus, commitment, and strong management; she warns that it is more difficult when collaborators are not geographically co-located. While virtual collaboration methods may help interactions at a distance, she notes that team co-location is likely to remain a powerful aspect of interdisciplinary research.

8.5 Individuals' contribution to evaluation and collective learning

(Micro / individual level)

Apart from stressing the importance of individual and team reflection on their work during the research process, little is written about how individuals contribute to evaluation of interdisciplinary research. Pennington *et al.* (2008) suggest that collective learning needs regular reports of progress from team members, and depends on constantly updating conceptual models. Evaluation literature indicates that including researchers and also stakeholders in evaluation design and implementation enhances both the research processes and the learning from the collaboration (Fazey *et al.*, 2013).

A number of survey comments related to how ID research could be assessed. Suggestions included that the context of when ID research does and does not work needs to be captured; the internal assessment process should use metrics that reflect investment in ID research; and that cost/benefit assessment should be used to measure value for money not just investment.

[24] Argyris, C. and Schon, D.A. (1996) Organizational learning II: theory, method, and practice. Addison Wesley, Reading, Mass. USA.

9 Disadvantages of an interdisciplinary approach

Our literature review focused more on the positive messages about how to do interdisciplinary research better, because we had reviewed the barriers to this approach in the Institute's Interdisciplinary Reading Group (IRG) during 2011 (Morris *et al.*, 2012). However, disadvantages of IDR were discussed in the interviews, and asked about in the staff survey. Understanding the disadvantages and limitations of an approach helps to identify ways to address them.

9.1 Interview results

The main disadvantages of an interdisciplinary approach identified by senior managers relate to the time it takes to get an interdisciplinary project started, and the costs associated with both getting a project going and being part of a larger team. Interdisciplinary teams are often instigated by big funders and may include a lot of external co-investigators, therefore costs and time of travel are increased. Issues about publishing were also raised. Challenges for successfully publishing interdisciplinary work included the relatively low impact factors of interdisciplinary journals, numbers of authors on papers, and difficulty in getting published when using different languages.

Another set of problems was raised about team working, which might relate to team work in general (e.g. making sure that people are on board, management issues, inclusion of everyone, building confidence in early career researchers). There seemed to be a perception that these issues may be exacerbated in interdisciplinary teams as it is more likely that ontological and epistemological barriers will exist, which may result in team members being less likely to communicate with each other effectively or being able to confidently air their views. Other challenges were also voiced, such as people being able to value other points of views, or being able to listen or understand them, as well as the ability of different disciplines to understand the robustness or validity of unfamiliar methodologies. Finally, there was a recognition that not all questions require to be answered using an interdisciplinary approach, and this should continue to be understood at the Institute.

External interviewees expressed similar shortcomings and challenges. If you spend your time learning new things – which is what has to happen if a researcher engages in interdisciplinary teams – you have less time "focusing on the thing that you can do best" such as delivering high impact disciplinary publications. This interviewee suggested that an ID researcher is likely to have a lower productivity: "I mean it [interdisciplinary research] is characteristically a way of producing very significant outputs but probably in smaller volume, although there are by-products along the way (…) But the difficulties that can stem from trying to see part of the purpose of doing an interdisciplinary project as being hitting deliverables that are to do with the measurement of academic performance is a real challenge." The second part of the quote hints at the challenges of traditional measures of academic impact which often do not capture the 'by-products' of interdisciplinary research.

Two external interviewees commented on the balance to be struck between encouraging interdisciplinarity and making sure that disciplines can develop the depth of knowledge. "We have to try to encourage an environment which is accepting and encouraging of interdisciplinary approaches (…) But at the same time we have to look after the health of the science base itself so you have to bring along everybody to some extent with you so there still has to be opportunity for the productive people who are not doing interdisciplinary science when it is worth having it." This links to the question of what kind of publication

strategy should be pursued. Some interviewees were unsure whether academic journals are best placed to publish interdisciplinary research because it does not fall neatly into certain boxes.

External interviewees also saw a need for a "critical mass of scientists in one discipline if you want to be an accepted authority on that … that science. You need that so that you can share that kind of expert knowledge between this critical body but also the training." This respondent believed that training staff internally is best, in particular if the organisation is already recognised as having the most advanced expertise in a particular field. Because the number of total staff is limited, there is a trade-off between how many staff from different disciplines can be employed while still maintaining that critical mass in one discipline.

The different vocabularies and terminologies used in different disciplines were recognised as a challenge to interdisciplinary working. One external interviewee expressed surprise that even between animal and plant scientists there were misunderstandings, and said that the need to develop a common language "did slow things down at first." Another can "imagine it could make a research project longer, there's the hassle of having to deal with people from different disciplines makes it more complicated, makes it a harder process, it can delay it."

Interdisciplinary research projects were seen to be bigger than disciplinary ones: "they require more people doing more things, putting in more structures and so on in place to make it all work." This was recognised to have cost implications, in one case referred to as 'frictional costs', brought about because time is needed for relationship building and "everything goes a bit slower because you've got to talk to one another all the time, if you get beyond a certain point you may be talking about needing a project manager." Interdisciplinary working can also "take longer because you're looking at more complex solutions (…) you potentially have people talking somewhat different languages. (…) [and] you may have a lot of negotiating to do to even reach the start point on a particular piece of work. (…) all of these things cost money in various ways so doing your work effectively on an interdisciplinary basis is potentially going to be more expensive."

In summary, the interviews highlighted that we need to acknowledge that:

- it is not necessary for all work to be interdisciplinary – some 'in-depth' questions are better answered by disciplinary teams or individuals;
- teams need to be nurtured to develop interdisciplinarity - being aware that it is important to value others' opinions, make everyone feel comfortable, allow more time for the project to be developed etc. – will aid this; and
- involvement in interdisciplinary teams needs to be considered in career evaluations, and team leaders need to allow early career researchers to be able to publish to help develop their own careers.

9.2 Staff survey results

A number of statements provided in the survey questionnaire (3, 11, 14 and 15) aimed to capture staff perceptions of challenges or barriers to ID research (full statements in Annex 1, Question 7). 64.5% of respondents agreed that teamwork in ID teams is more challenging, and 57.9% agreed that this type of research requires more time than disciplinary work. Similarly, 59.2% agreed that leading disciplinary research is easier than for interdisciplinary work, and 63.2% thought that disciplinary expertise is more easily valued. These results reflect a considerable convergence of opinions, and an awareness of issues related to interdisciplinary research.

Respondents' comments also showed their awareness of issues associated with interdisciplinary research, in particular with regard to publishing and ultimately career evaluation and progression.

Comments included:

- Forcing people to work interdisciplinarily may be counterproductive and demotivating
- Not all researchers have the attitudes/skills needed for ID research
- It is harder to produce well-reviewed journal papers from interdisciplinary work than disciplinary work
- Dissemination of ID research is more time consuming and demanding than for disciplinary research
- ID research does not sit so well within current career structures for academics
- Current publishing culture rewards disciplinary more than interdisciplinary researchers.

A further set of barriers was identified at the institute level. Survey respondents emphasised that there is already a lot of ID research being undertaken at the Institute. Nevertheless, a number of comments were made regarding barriers to interdisciplinary research. These are in addition to barriers at the individual and team level reported in the previous paragraph.

Some comments indicated that there are not enough activities to support interdisciplinary research at the Institute; for example, there was disappointment that the Hutton gathering appeared as a one-off. The recent (enforced) lab and office moves (referring to autumn 2013) hindered interdisciplinary work and wasted time. The design of research plans (referring to ecosystem services research) is seen to "separate out WPs into distinct sectors/disciplines" and as not conducive to interdisciplinary research. A further comment criticised "the 'who is paying for your time' mantra that still seems to be expressed a lot" as very damaging because it stifles "the very serendipitous connections between people/projects that an 'interdisciplinary culture' should be trying to foster." Management structures were seen by some respondents as facilitating more hierarchical workplace interactions that create difficulties in accessing resources from other disciplines when needed. Organisational structures were also seen by some respondents to reproduce disciplinary barriers.

10 Survey of James Hutton Institute staff: additional results

10.1 Who responded to the survey?

There were a total of 81 responses to the survey. Five questionnaire respondents who did not reach the final page of the online survey were not included in the analysis. Amongst respondents who reached the end of the survey, some left blank fields, but these respondents were not removed from the sample in order to obtain as much information as possible. This is why the results show different sample sizes for each of the separate analyses.

The pool of respondents (Figure 7) covered a broad range of ages, with the majority between 40 and 49 years old (34.2%). There were slightly more men in the sample (52.0%).

All science groups within the Institute were represented and we included BioSS as a science group in the analyses) (Figure 8). Social, economic and geographical scientist respondents were most strongly represented, which might indicate a disciplinary affiliation to the topic, or openness to interdisciplinary work or that social scientists are more likely to complete surveys. However, this result could also be linked to the fact that three of the five DICE researchers are from this group, so possibly SEGS staff had greatest awareness of the survey within the Institute.

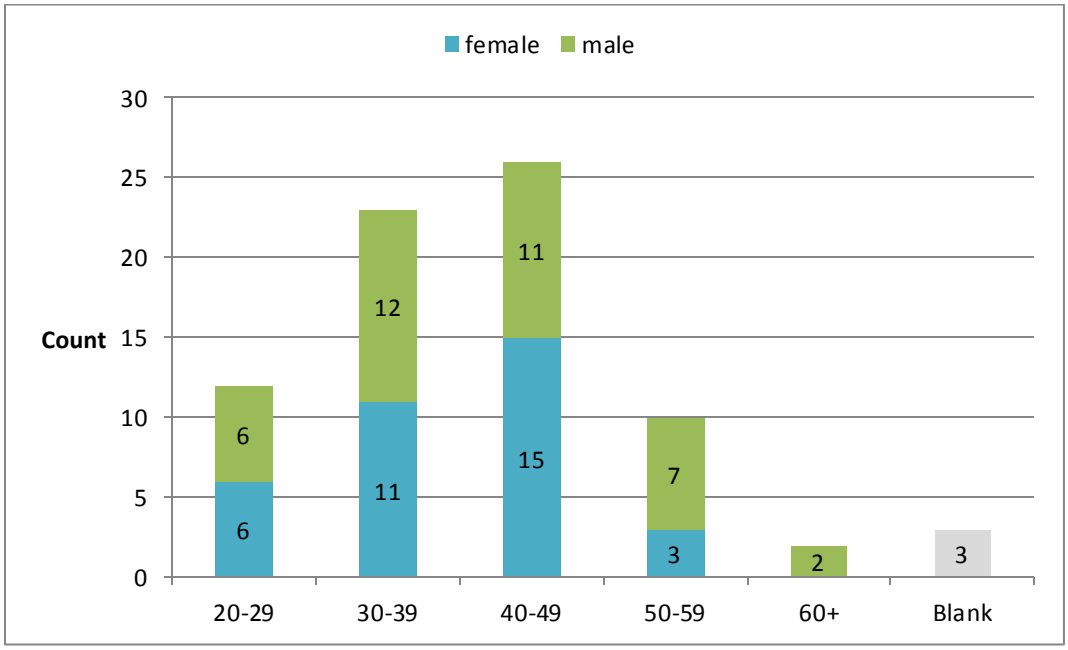


Figure 7: Age and gender of respondents (n=76)

10.2 How representative is the survey of the wider Institute staff?

Figure 8 shows the total number of staff[25] excluding PhD students of each science group, and the number of staff who completed the survey (n=76). According to these figures, the survey had a response rate of 20.0 %.

Due to the small sample size and the unbalanced share of respondents per group (55.6% of SEGS compared to 10.4% of Cell and Molecular Sciences), we acknowledge that the survey results should not be treated as representative of the whole Institute. Results may be biased due to self-selection of respondents, ie we may ass e that the sample includes those people who feel most strongly (positively or negatively) about interdisciplinary research and wanted to express their opinion, and that staff involved in IDR may have been more likely to respond. These assumptions are supported by the free text responses and the responses to the question on what share of people's work is interdisciplinary (Figure 9).

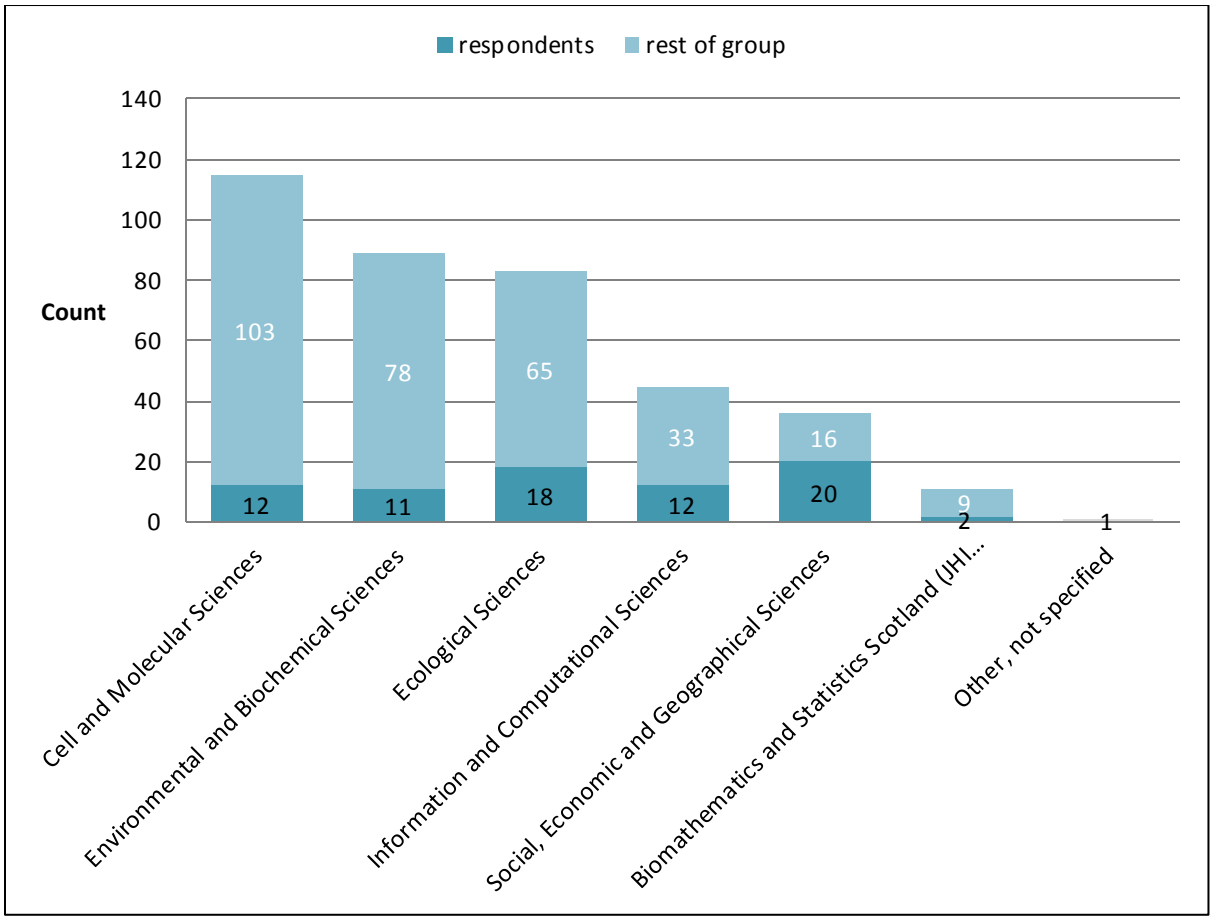


Figure 8: Number of staff in James Hutton Institute groups compared with number of survey respondents (n=76)

[25] As of 2013, provided in the ACS review documents of the five science groups; the figure for BioSS includes the 11 non-admin members of BioSS based at the James Hutton Institute's Aberdeen and Dundee sites as stated on the BioSS website.

10.3 What is the 'level' of interdisciplinarity in the Institute?

The majority of respondents (84.2%) currently work with others on interdisciplinary projects or have had such experience in the past. Of this percentage, 62.5% reported that their interdisciplinary experience combined natural and social science methodologies or approaches. However, this figure increases if the definition is not confined to cooperation among only social and natural scientists but also includes, for example, information and computational sciences.

We found no association between interdisciplinary working and age, gender, or time worked at the Institute (for more details see Annex 4).

Regarding the proportion of interdisciplinary to disciplinary working, there appears to be a divide with 32.9% of respondents spending less than half or none of their time on ID work, and 31.6% spending more than half of or all of their time on interdisciplinary work (Figure 9). There is no strong association between time worked at the Institute and responses to this question. 17.1% of the respondents did not reply to this question which might be reflecting a difficulty in identifying interdisciplinarity when it comes to practice.[26]

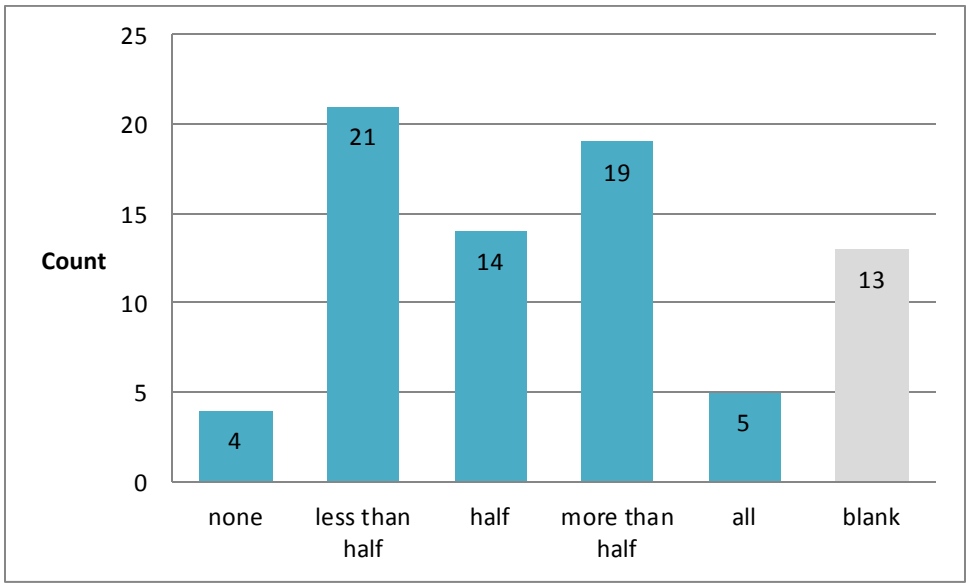


Figure 9: At present, approximately what share of your work (referring to time worked) is of an interdisciplinary nature? (n=76)

When asked whether the extent of respondents' involvement in interdisciplinary research had changed during their time at the Institute, 36.8% stated that it had remained constant over time. 27.6% had become more involved in interdisciplinary research, and 10.5% were less involved now than in the past (Figure 10).

[26] Note the following contradictory responses: four participants responded 'None' to this question (question 4), while 12 reported not having experience in working on interdisciplinary projects (question 2).

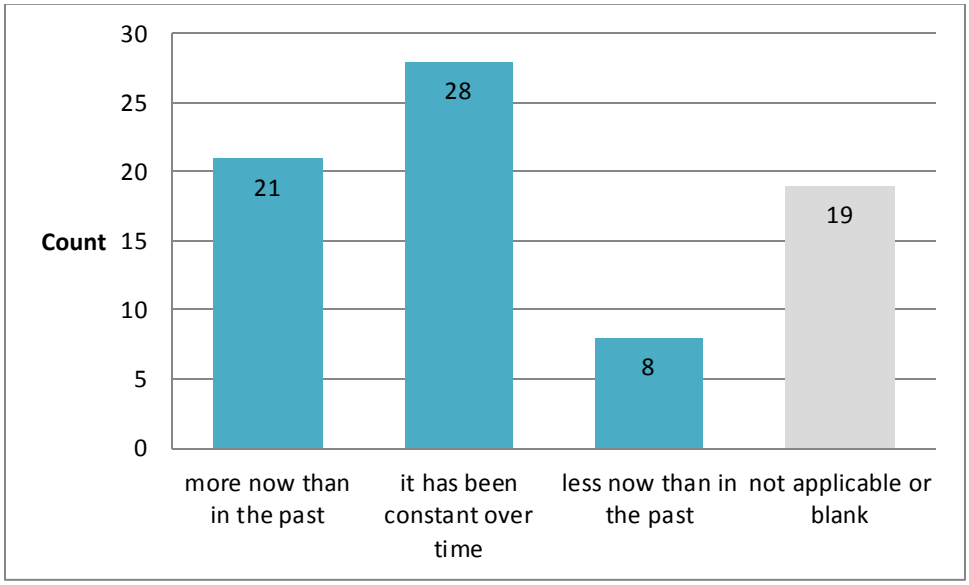


Figure 10: Involvement in interdisciplinary research over time (n=76)

This pattern was consistent across the different ranges of years respondents have worked at the Institute, except for those who had less than 1 year of service, or between 8-9 years of service, who mainly reported that their involvement had increased, and those having between 25-29 years of service, where one respondent reported that their share of IDR had been constant, while the other reported less involvement over time.

The figures and respondents' assessments reported in this section need to be seen in the context of their understanding of interdisciplinarity. This understanding varied widely among staff, as shown in the following section.

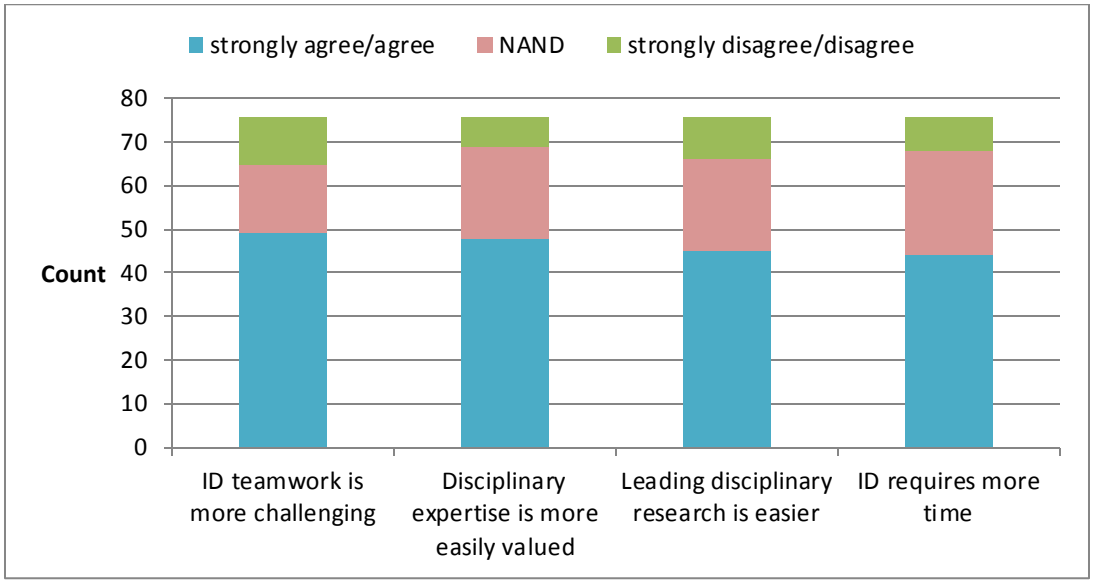


Figure 11: Responses to statements capturing challenges and barriers to ID research (n=76)

10.4 Comments on interdisciplinarity at the Institute

This section summarises the comments from the free text box at the end of the DICE survey questionnaire, plus two written comments received by the DICE team separately. Of the total number of survey respondents, 35 made free text comments. Four of these just said 'no further comments' so these 4 are not included in the analysis. Therefore, 31 comments from the questionnaire plus two additional comments received separately have been analysed (n=33) and the content categorised in five groups. Note that some responses covered more than one category (4). The characteristics (age, gender) of the respondents who provided comments are included in Annex 3.

Table 6: Comments by category (n=44)

Comments made by category	44
About interdisciplinary research	17
Institute related	13
Survey related	8
DICE related	2
Additional personal information	3

The comments are summarised (paraphrased) by category to illustrate the points raised by the respondents. We have omitted reporting on comments relating to the survey itself but have noted these to consider for any similar survey in the future, and have responded to some concerns raised in section 2. We also do not report on additional personal information and DICE-related comments but took note of the suggestions made. Comments relating to the matrix management structure are included in section 7 on supportive conditions.

10.5 Conclusions

Results of the DICE survey of James Hutton Institute staff should not be treated as representative of the whole Institute. Nevertheless, a snapshot of interdisciplinary research at the Institute emerges from the findings, with survey responses showing diverse understandings of interdisciplinarity. The majority of respondents (59%) understand interdisciplinarity to be research that integrates different disciplines working towards a jointly set objective, rather than working independently under a thematic umbrella, and not (necessarily) involving non-academic participants.

These different understandings greatly influence the assessment of how much of their research individuals would label as interdisciplinary. In order to capture 'levels' of interdisciplinarity within the Institute, we recommend the Institute adopts a working definition of interdisciplinarity that acknowledges its different forms (broad and narrow), supported by a list of example disciplines. We argue that any attempt at 'measuring' levels of interdisciplinary research at the Institute would produce a more accurate picture if all staff and managers used the same definition.

Based on such a shared definition, we recommend repeating the survey at regular intervals (e.g. several years) and to include the same questions every time, including:

- current or past work on interdisciplinary projects;

- combinations of natural and social science methodologies or approaches, potentially expanding to combinations with information and computational sciences;
- share of work (referring to time worked) with an interdisciplinary nature; and
- extent of involvement in interdisciplinary research since the last survey.

We found that younger respondents tended to have less experience of working in interdisciplinary projects. Our findings do not reveal why that might be the case. A plausible explanation is that they have mainly worked on their PhD project which is an individual undertaking that does not lend itself to interdisciplinary collaboration.

There is considerable awareness of the challenges and benefits of interdisciplinary research among survey respondents, along with the personal attitudes, skills, and wider conditions needed to support this type of research. Although we cannot claim that the survey is representative of all Institute staff, we believe there is enormous potential and support for interdisciplinary research, evidenced by the data on how many people have been involved in narrow or broad interdisciplinary projects recently.

11 Developing a comprehensive framework for interdisciplinary research

A substantial body of work from different academic spheres has been developed, revealing insights into interdisciplinary research (IDR). However the literature shows that there is no overarching theoretical framework for the study of IDR, its implementation, or its effectiveness. As yet, there is no widely agreed theoretical basis for IDR, although there is increasing interest in this type of research, and more research that claims to exemplify this approach. Our review included Bammer's approach to constructing such a framework to underpin high quality IDR.

Increasingly, insights on interdisciplinary research are being provided by a range of different perspectives. Bammer (2013a:4) lists what she calls 'related approaches': post-normal science; systemic intervention; integrated assessment; sustainability science; team science; mode 2; and action research. She notes, however, that these various approaches rarely adopt definitions of interdisciplinarity from the theoretical literature, and don't generally learn from each other's work.

Bammer (2013a:3) argues that interdisciplinary research tends to be marginalized by academia, despite the increasing advocacy of its use to address social and environmental problems. This is largely due to the fragmented nature of the field, which means that insights are not widely shared or doc ented, and cannot be systematically built on. She further argues that there is no comprehensive guidance for interdisciplinary researchers on how to make fundamental decisions about which disciplines should be included in the research, how each discipline should contribute to the work, and how to integrate findings from different disciplinary approaches and methods.

Bammer (2013a:4), however, believes that sufficient levels of experience and conceptual development now exist to begin to reformulate thinking about what interdisciplinarity actually is, and to develop ways of conducting this research. Connections can be made across different areas of studies (eg health / environment studies) to give new insights into useful theories and methods, and progress made by linking theoretical and practical developments.

Bammer (2013a:5) develops a comprehensive framework for interdisciplinary research on 'complex real-world problems'. It addresses current fragmented and unorganised fields by:

- Building on both theoretical and experiential developments arising from the various interdisciplinary approaches;
- Enabling widespread and substantial exchange of interdisciplinary ideas and methods; and
- Collecting and evaluating these methodologies.

Framework development is based on 4 arguments, that:

1. A specific focus is needed to encompass the variety of terms and meanings used in the field; this is to be on 'research that involves experts from multiple, diverse disciplines working together on a complex real-world problem.

2. There is no single best approach to such research; multiple options are available and these can be viewed as a specific research style- 'integrative applied research'.
3. There is a new discipline of Integration and Implementation Sciences (I2S) which allows for effective doc enting and sharing of concepts and methods for integrative applied research.
4. Relevant material can be obtained from myriad research projects but this would be too time-cons ing given the urgency of current socio-environmental problems. Progress in integrative applied research should be via a new 'Big Science' project, such as the H an Genome and Manhattan Projects- a I2S Development Drive.

In brief, Bammer's framework starts with the three domains she identifies as characterising the integrative applied research approach and the discipline of I2S (2013a:15):

- Synthesis of disciplinary and stakeholder knowledge;
- Understanding and managing of diverse unknowns; and
- Provision of integrated research for change in policy and practice.

Further drilling down in these three domains leads to the five question framework she proposes (2013a:21):

1. What is the integrative applied research aiming to achieve and who is intended to benefit?
2. What is the integrative applied research dealing with- that is, which knowledge is synthesised, unknowns considered and aspects of policy targeted?
3. How is the integrative applied research undertaken (the knowledge synthesised, diverse unknowns understood and managed, and integrated research support provided), by whom and when?
4. What circumstances might influence the integrative applied research?
5. What is the result of the integrative applied research?

12 DICE recommendations

Our findings were synthesised in the form of recommendations for the Institute, grouped into four areas. Our findings highlighted the crucial role of effective and efficient communication for IDR and this is linked to and important for all of the four areas.

1. Interdisciplinary research needs longer to plan and do. This needs to be recognised in project work plans and costings, including the extra time needed for arriving at a shared understanding of the problem and potential solutions, developing a common language, and training team members who are not experienced in interdisciplinary working.

2. There is a need to enhance opportunities for discussion and sharing of experience and knowledge, both formal and informal:
    a. Formally, the format of existing Institute seminars needs to be reviewed to assess if they are supporting IDR, and improved. More discussion time (rather than pure presentations) would allow more knowledge sharing, initial project ideas should be presented to get feedback from other disciplines, and lessons from good interdisciplinary projects could be shared. In addition, retreats, crucible-style events, whole Institute events (gatherings) and knowledge exchange events with key stakeholders would support internal and external knowledge exchange
    b. Informally, sharing of experience could be enhanced by improving physical spaces, and creatively providing opportunities for socialising and discussions

3. The Institute's management structure and processes need to better support IDR:
    a. Clear incentives and rewards for doing interdisciplinary research from senior managers and the Executive
    b. Periodical reviews of the structure and operation of the Hutton matrix
    c. Developing indicators for monitoring IDR, beyond the currently-used distinction of social and natural sciences, including working with funders on appropriate indicators and capturing by-products of IDR
    d. An effective and efficient information system that harnesses existing technologies would allow staff to see current and previous projects carried out in the Institute
    e. Development and training opportunities to increase skills in IDR, including work shadowing, and practice in interdisciplinary teams, in particular for the next generation of IDR leaders

4. There needs to be greater awareness that interdisciplinarity is dependent on project design and project leadership/ management. Individuals' capacity to review interdisciplinary proposals, projects and manuscripts needs to be developed, possibly through discussions with colleagues or specific training. There is scope to deliver more effective interdisciplinary research if proposals for large funding bids (such as the 5 year Scottish Government Strategic Research Programme) are carefully designed to meet this goal, and more than one principal investigator established for projects where appropriate. At team level, leaders need to agree team roles, research themes, and communication processes to help the team gain clarity. Individuals, in turn, need to be assertive about their needs and resources to fulfil their roles.

13 References

Aboelela SW, Larson E, Bakken S, Carrasquillo O, Formicola A, Glied SA, Haas J, Gebbie KM. (2007) 'Defining Interdisciplinary Research: Conclusions from a Critical Review of the Literature'. *Health Services Research* 42 (1): 329-346

Aslin and Blackstock (2010) 'Now I'm not an expert in anything': challenges in undertaking transdisciplinary inquiries across the social and biophysical sciences' in Brown, V.A., Harris, J.A., Russell, J.Y. (eds) *Tackling wicked problems through the transdisciplinary imagination*, Earthscan, London, pp117-130

Bammer, Gabriele (2008) *Enhancing research collaborations*, Integration Insights Number 10, The Australian National University, http://i2s.anu.edu.au/sites/default/files/integration-insights/integration-insight_10.pdf

Bammer, Gabriele (2013a) *Disciplining Interdisciplinarity: Integration and Implementation Sciences for Researching Complex Real-World Problems*, ANU E-Press, (chapters 1 and 2) free book online, http://epress.anu.edu.au/titles/disciplining-interdisciplinarity

Bammer, Gabriele (2013b) *Collaboration = Harnessing and Managing Difference*, Poster prepared at First Global Conference on Research Integration and Implementation, Australian National University/CEPS, http://i2sconference.digitalposter.com.au/posters-search/

Barker, P. (2007) Music, in Canning (ed) *Disciplines in dialogue: Disciplinary perspectives on interdisciplinary teaching and learning*, the Interdisciplinary Teaching and Learning Group, Subject Centre for Languages, Linguistics and Area Studies, School of humanities, University of Southampton, https://www.llas.ac.uk/resourcedownloads/3219/disciplines_in_dialogue.pdf

Bentley, S. (2007) English, in Canning (ed) *Disciplines in dialogue: Disciplinary perspectives on interdisciplinary teaching and learning*, the Interdisciplinary Teaching and Learning Group, Subject Centre for Languages, Linguistics and Area Studies, School of humanities, University of Southampton, https://www.llas.ac.uk/resourcedownloads/3219/disciplines_in_dialogue.pdf

Burd, L. (2007) Information and Computer Sciences, in Canning (ed) *Disciplines in dialogue: Disciplinary perspectives on interdisciplinary teaching and learning*, the Interdisciplinary Teaching and Learning Group, Subject Centre for Languages, Linguistics and Area Studies, School of humanities, University of Southampton, https://www.llas.ac.uk/resourcedownloads/3219/disciplines_in_dialogue.pdf

Canning, J. (2007) Introduction, in Canning (ed) *Disciplines in dialogue: Disciplinary perspectives on interdisciplinary teaching and learning*, the Interdisciplinary Teaching and Learning Group, Subject Centre for Languages, Linguistics and Area Studies, School of humanities, University of Southampton, https://www.llas.ac.uk/resourcedownloads/3219/disciplines_in_dialogue.pdf

Chettiparalamb, A. (2007) *Interdisciplinary literature review*, the Interdisciplinary Teaching and Learning Group, Subject Centre for Languages, Linguistics and Area Studies, School of humanities, University of Southampton, http://www.heacademy.ac.uk/assets/documents/sustainability/interdisciplinarity_literature_review.pdf

Cunliffe, L. (2007) Art Education, in Canning (ed) *Disciplines in dialogue: Disciplinary perspectives on interdisciplinary teaching and learning*, the Interdisciplinary Teaching and Learning Group, Subject Centre for Languages, Linguistics and Area Studies, School of humanities, University of Southampton, https://www.llas.ac.uk/resourcedownloads/3219/disciplines_in_dialogue.pdf

Davies, Martin and Devlin, Marcia (2007) *Interdisciplinary higher education: Implications for teaching and learning*, University of Melbourne.

Derounian (2007) Community Development, in Canning (ed) *Disciplines in dialogue: Disciplinary perspectives on interdisciplinary teaching and learning*, the Interdisciplinary Teaching and Learning Group, Subject Centre for Languages, Linguistics and Area Studies, School of humanities, University of Southampton, https://www.llas.ac.uk/resourcedownloads/3219/disciplines_in_dialogue.pdf

Derrick, Edward G., Falk-Krzesinski, Holly J., Roberts, Melanie R. (eds), Olson, Steve. (technical writer) (2011) *Facilitating Interdisciplinary Research and Education: A Practical Guide*, American Association for the Advancement of Science, http://www.aaas.org/cspsp/interdisciplinary/guide/Full_Report.pdf

Evely, A.C., Fazey, I., Stringer, L.C., Reed, M.S. (2012) *Designing knowledge exchange for resilience: how people view and conduct knowledge matters*. Sustainable Learning Working Paper Series No.2, http://sustainable-learning.org/wp-content/uploads/2012/01/Evely-et-al-2012-Sustainable-Learning-Working-Paper-Series-No.-2.pdf

Evely, A.C., Lambert, E., Reed, M. and Fazey, I. (2013) *Evaluating knowledge exchange: a review*, Centre of Expertise for Waters (CREW) and St Andrews University, http://www.crew.ac.uk/projects/evaluating-science

Funtowicz, S.O. and Jerome R. Ravetz. 1991. 'A New Scientific Methodology for Global Environmental Issues' in Robert Costanza (ed) *Ecological Economics: The Science and Management of Sustainability*,. New York: Col bia University Press: 137-152.

Grigg, Johnston & Misom (2003) *Emerging issues for cross-disciplinary research. Conceptual and Empirical Dimensions*. Report published by the Commonwealth Department of Education Science & Training. Canberra, Australia

Haynes, C. (2002) 'Introduction: Laying a Foundation for Interdisciplinary Teaching' in Haynes, C. (ed) *Innovations in Interdisciplinary Teaching*. Washington: American Council on Education / Oryx Press

Hellstrom, T., Jacob, M. and and Wenneberg, S.B. (2003) 'The discipline of post-academic science: reconstructing the paradigmatic foundations of a virtual research institute'. *Science and Public Policy*, vol e 30, number 4, August 2003, pages 251–260, Beech Tree Publishing, 10 Watford Close, Guildford, Surrey GU1 2EP, England

Klein, Julie Thompson (2004) 'Prospects for transdisciplinarity'. *Futures* 36, 515-526

Klein, Julie T. (2008) 'Evaluation of Interdisciplinary and Transdisciplinary Research'. A Literature Review, *Am J Prev Med* 35 (2S):S116 –S123

Kragt, M.E., Robson, B.J. and Macleod, C.J.A. (2013) 'Modellers' roles in structuring integrative research projects'. *Environmental modelling and software*, 39(1): 322-330.

Lyall, Catherine, Bruce, Ann, Marsden, Wendy, Meagher, Laura (2013) 'The role of funding agencies in creating interdisciplinary knowledge'. *Science and Public Policy* Vol 40 No. 1, pp62-71

Lyall, Catherine, Bruce, Ann, Tait, Joyce, Meagher, Laura (2011) *interdisciplinary Research Journeys: Practical Strategies for Capturing Creativity*, London: Bloomsbury

Lyall, Catherine (2008) *A Short Guide to Designing Interdisciplinary Research for Policy and Practice*, ISSTI Briefing Note (Number 6) November 2008, http://www.issti.ed.ac.uk/__data/assets/file/0010/77608/ISSTI_ID_Briefing_Note_6_ID_research_for_policy_and_practice.pdf

Lyall, Catherine and Meagher, Laura (2007) *A Short Guide to Building and Managing Interdisciplinary Research Teams*, ISSTI Briefing Note (Number 3) September 2007, http://www.issti.ed.ac.uk/__data/assets/file/0007/77605/ISSTI_Briefing_Note_3_ID_teams.pdf

Mâsse, Louise C., Moser, Richard P., Stokols, Daniel, Taylor, Brandie K., Marcus, Stephen E., Morgan, Glen D., Hall, Kara L., Croyle, Robert T., Trochim, William M. (2008) 'Measuring Collaboration and Transdisciplinary Integration in Team Science'. *Am J Prev Med* 2008;35(2S)

Meagher, L. (2012) *Report on Rural Economy and Land Use Programme (Relu) Societal and Economic Impact Evaluation*, ESRC, http://www.relu.ac.uk/news/Evaluation.htm

Montanari, A., Young, G., Savenije, H.H.G., Hughes, D., Wagener, T., Ren, L.L., Koutsoyiannis, D., Cudennec, C., Toth, E., Grimaldi, S., Blöschl, G., Sivapalan, M., Beven, K., Gupta, H., Hipsey, M., Schaefli, B., Arheimer, B., Boegh, E., Schymanski, S.J., Di Baldassarre, G., Yu, B., Hubert, P., Huang, Y., Sch ann, A., Post, D., Srinivasan, V., Harman, C., Thompson, S., Rogger, M., Viglione, A., McMillan, H., Characklis, G., Pang, Z., and Belyaev, V. (2013) 'Panta Rhei—Everything Flows": Change in hydrology and society—The IAHS Scientific Decade 2013–2022', *Hydrological Sciences Journal*. 58 (6) 1256–1275, http://www.tandfonline.com/doi/full/10.1080/02626667.2013.809088#tabModule

Morris, S., Currie, M., Holmes, B., MacLeod, K., Prager, K. and Waylen, K. (2012) *Summary of literature reviewed by the James Hutton Institute interdisciplinary reading group*, DICE, the James Hutton Institute.

Morrow, K. (2007) Law, in Canning (ed) *Disciplines in dialogue: Disciplinary perspectives on interdisciplinary teaching and learning*, the Interdisciplinary Teaching and Learning Group, Subject Centre for Languages, Linguistics and Area Studies, School of Humanities, University of Southampton, https://www.llas.ac.uk/resourcedownloads/3219/disciplines_in_dialogue.pdf

Morse, W.C., Nielsen-Pincus, M., Force, J., Wulfhorst, J.D. (2007) 'Bridges and Barriers to Developing and Conducting Interdisciplinary Graduate-Student Team Research'. *Ecology and Society* 12(2), http://www.ecologyandsociety.org/vol12/iss2/art8/

Naiman, Robert J. (1999) 'A Perspective on Interdisciplinary Science'. *Ecosystems* 2: 292–295 School of Fisheries, University of Washington, USA

Newing H. (2010). 'Interdisciplinary training in environmental conservation: definitions, progress and future directions'. *Environmental Conservation* 37 (4): 410-418.

Nissani, Moti (1997) 'Ten Cheers for Interdisciplinarity: The Case for Interdisciplinary knowledge and Research'. *The Social Science Journal* Vol. 34, No. 2: pp201-216.

Penlington, R. (2007) Engineering, in Canning (ed) *Disciplines in dialogue: Disciplinary perspectives on interdisciplinary teaching and learning*, the Interdisciplinary Teaching and Learning Group, Subject Centre for Languages, Linguistics and Area Studies, School of Humanities, University of Southampton, https://www.llas.ac.uk/resourcedownloads/3219/disciplines_in_dialogue.pdf

Pennington, Deanna D. (2008) 'Cross-Disciplinary Collaboration and Learning'. *Ecology and Society* 13(2): 8

Repko, Allen F (2012) Interdisciplinary research: Process and theory, (2nd edn) SAGE publications Ltd.

Sánchez-Colberg (2007) Dance, in Canning (ed) *Disciplines in dialogue: Disciplinary perspectives on interdisciplinary teaching and learning*, the Interdisciplinary Teaching and Learning Group, Subject Centre for Languages, Linguistics and Area Studies, School of Humanities, University of Southampton, https://www.llas.ac.uk/resourcedownloads/3219/disciplines_in_dialogue.pdf

Sommer, R. (2000) *'Discipline and Field of Study: A search for clarification'. Journal of Environmental Psychology* 20, 1^4 0272-4944/00/010001+04 $35.00/0 # 2000 Academic Press doi:10.1006/jevp.1999.0168, http://www.idealibrary.com *University of California, Davis, USA*

Stokols, Daniel, Hall, Kara L., Taylor, Brandie K., Moser, Richard P. (2008) 'The Science of Team Science: Overview of the Field and Introduction to the Supplement', *American Journal of Preventive Medicine* Vol e 35, Issue 2, Supplement , ppS77-S89, http://cancercontrol.cancer.gov/brp/scienceteam/ajpm_complete.pdf as presented in Transdisciplinarity and Team Science (2011), Stokols article on science of team science http://news.uci.edu/features/science-of-team-science-revealed/

Tress B, Tress G, van der Valk A, Fry G, (eds) (2003) *Interdisciplinary and Transdisciplinary Landscape Studies: Potential and Limitations*. Wageningen

Tress, G., Tress, B. and Fry, G. (2004) 'Clarifying integrative research concepts in landscape ecology'. *Landscape Ecology* 20: 479–493

Winder, N. (2003) 'Successes and problems when conducting interdisciplinary or transdisciplinary (= integrative) research'. pp 74-90 in B. Tress, G. Tress, and G. Fry, (eds) *Potential limitations of interdisciplinary and transdisciplinary landscape studies*. Delta Series 2. Alterra Green World Research and Wageningen University, Wageningen, The Netherlands

14 Annexes

Annex 1: Questionnaire for survey of JHI research staff

0. Are you a member of staff at the James Hutton Institute

◯ yes
◯ no

1. Which of the following statements comes closest to your understanding of interdisciplinary research? *(choose one of the following answers)*

◯ Research that involves different disciplines working towards a number of objectives under one thematic umbrella

◯ Research that integrates different disciplines, working towards a jointly set objective

◯ Research that integrates different disciplines and non-academic participants, working towards a jointly set objective

2. Have you experience of working with others on interdisciplinary projects now or in the past?

◯ yes → **go to question 3**
◯ no → **skip to question 7**

3. Have any of these interdisciplinary projects combined natural and social science methodologies or approaches?

◯ yes
◯ no

4. At present, approximately what proportion of your work (referring to time worked) is of an interdisciplinary nature? *(Choose one of the following answers)*

none	less than half	half	more than half	all
◯	◯	◯	◯	◯

5. During your time at the Institute, has the extent of your involvement in interdisciplinary research changed? *(Choose one of the following answers)*

◯ more now than in the past
◯ it has been constant over time
◯ less now than in the past
◯ not applicable

6a. For the most recent interdisciplinary project that you have worked on, what is/was its topic?

_____

6b. For the most recent interdisciplinary project that you have worked on, what disciplines were involved?

7. Here are some statements about interdisciplinary research, with which you may or may not agree. Please indicate the extent to which you agree or disagree with each of the following statements.

	strongly agree	agree	neither agree nor disagree	disagree	strongly disagree
1) Good interpersonal communication is vital for productive interdisciplinary research.	○	○	○	○	○
2) Multidisciplinarity and interdisciplinarity mean the same thing.	○	○	○	○	○
3) Teamwork is more challenging in interdisciplinary projects, compared to disciplinary projects.	○	○	○	○	○
4) Interdisciplinary research usually has less scientific depth.	○	○	○	○	○
5) Interdisciplinary research does not require everyone to have a common language.	○	○	○	○	○
6) Working in different work environments enhances the individual's capacity for interdisciplinary research.	○	○	○	○	○
7) Any complex problem facing society today requires interdisciplinary research.	○	○	○	○	○
8) Anybody can do interdisciplinary research regardless of their communication skills.	○	○	○	○	○
9) Non-academics need to be involved from the beginning to make research transdisciplinary.	○	○	○	○	○
10) Interdisciplinary research is not necessary to address less complex environmental problems.	○	○	○	○	○
11) Interdisciplinary research projects require more time than disciplinary research projects	○	○	○	○	○
12) Interdisciplinary teams require some disciplinary experts	○	○	○	○	○
13) Through interdisciplinary research, we can increase the validity of results.	○	○	○	○	○
14) Disciplinary research expertise is more easily valued in career evaluations than interdisciplinary expertise	○	○	○	○	○
15) Leading disciplinary research compared to interdisciplinary research is easier	○	○	○	○	○
16) Arriving at a shared understanding of the problem is crucial in interdisciplinary research	○	○	○	○	○
17) Informal interactions (e.g. in the canteen) act as a catalyst to interdisciplinary research	○	○	○	○	○
18) The matrix management structure supports interdisciplinary research	○	○	○	○	○
19) Interdisciplinary research has the potential to produce more multifaceted and diverse outputs than disciplinary research	○	○	○	○	○

8. Can you think of anything that has improved your ability to do interdisciplinary research?

◯ no

◯ yes → **8a. If yes, what? (e.g. any particular experience, or type of support)?**

And lastly, a few questions about your background and work environment, as various personal and professional experiences are sometimes thought to influence attitudes to interdisciplinarity. We would very much appreciate if you would answer all the questions. These data are collected solely for analysis purposes, and no information will be personally identifiable.

9a. We are interested in your disciplinary background as well as your current expertise.
a) In which disciplines did you earn your qualifications (degrees)?

Bachelor-level qualification(s):	
Master-level qualification(s):	
Doctoral-level qualification(s):	

9b. To which disciplinary area(s) would you allocate your current scientific expertise?

10. Have you always worked in academia? (excluding part-time jobs during studies)

◯ yes ◯ no

11 How long have you worked at the James Hutton Institute (in years)? *[range of selection given]*

12. Which James Hutton Institute Science Group do you work in? *(choose one of the following answers)*

◯ Cell and Molecular Sciences
◯ Environmental and Biochemical Sciences
◯ Ecological Sciences
◯ Information and Computational Sciences
◯ Social, Economic and Geographical Sciences
◯ Other: _____

13. Have you worked in projects involving staff from the following Science Groups within the Institute?*(please tick as many as apply)*

◯ Cell and Molecular Sciences
◯ Ecological Sciences
◯ Environmental and Biochemical Sciences
◯ Information and Computational Sciences
◯ Social Economic and Geographical Sciences

14. Which Institute themes and centres are you affiliated with? *(Check any that apply)*

- ◯ Safeguarding Natural Capital
- ◯ Enhancing Crop Productivity and Utilisation
- ◯ Delivering Sustainable Production Systems
- ◯ Controlling Weeds, Pests and Diseases
- ◯ Managing Catchments and Coasts
- ◯ Realising Land's Potential
- ◯ Nurturing Vibrant and Low Carbon Communities
- ◯ CREW
- ◯ CXC
- ◯ EPIC
- ◯ Other:

15. Please indicate your age group

◯ 20-29 ◯ 30-39 ◯ 40-49 ◯ 50-59 ◯ 60+ ◯ Other

16. Please indicate your gender

- ◯ male
- ◯ female

17. Do you have any other comments on the topic of the survey?

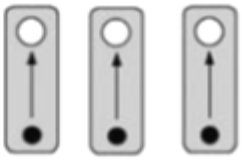
Thankyou!

Annex 2: DICE working definition of interdisciplinarity

In order to capture the understandings of interdisciplinarity among staff, we developed three answer options based on an overview of research concepts: disciplinarity, multidisciplinarity, interdisciplinarity, and transdisciplinarity developed by Tress *et al*. (2004, p484).

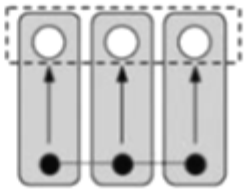
Disciplinarity

- Within one academic discipline
- Disciplinary goal setting
- No cooperation with other disciplines
- Development of new disciplinary knowledge and theory



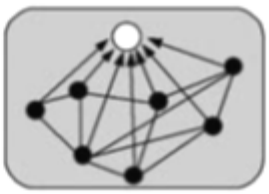
Multidisciplinarity

- Multiple disciplines
- Multiple disciplinary goal setting under one thematic umbrella
- Loose cooperation of disciplines for exchange of knowledge
- Disciplinary theory development



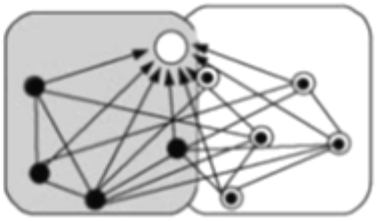
Interdisciplinarity

- Crosses disciplinary boundaries
- Common goal setting
- Integration of disciplines
- Development of integrated knowledge and theory



Transdisciplinarity

- Crosses disciplinary and scientific/academic boundaries
- Common goal-setting
- Integration of disciplines and non-academic participants
- Development of integrated knowledge and theory among science and society



- discipline
- non-academic participants
- goal of a research project
- movement towards goal
- cooperation
- integration

- thematic umbrella
- academic knowledge body
- non-academic knowledge body

Annex 3: Methodology for analysing broad and narrow interdisciplinarity

Interdisciplinarity is defined differently by different people. Responses to the question of which disciplines a recent interdisciplinary project combined showed a wide variety of disciplines and domains to which these disciplines could be allocated. We therefore decided to distinguish between broad and narrow interdisciplinarity.

For the analysis of broad and narrow interdisciplinarity, two researchers in the DICE team independently classified the disciplinary background of individuals, as well as the disciplines involved in a recent interdisciplinary project as provided by the respondent. Our definition of broad interdisciplinarity referred to projects that involved a combination of at least two domains. Our domains were: social sciences; natural sciences; information and computational sciences; humanities; and statistics. We classified bioinformatics as an interdisciplinary science in its own right (although not a domain). Engineering was not classified as a natural science, but if that discipline cooperated with natural sciences we classified it as narrow interdisciplinarity; if engineering cooperated with social science or information and computational science we classified it as broad.

We also made the following assumptions:

- 'Modelling' is a tool rather than a discipline, but if it was involved in a project we classified it as a broad ID project (except if the only other discipline involved was information and computational sciences);
- 'Remote sensing', 'mapping', '' and 'GIS' we defined as parts of information and computational sciences;
- 'Law' and 'education studies' we defined as social science.

Annex 4: Age and Gender of respondents who provided comments on interdisciplinarity in the survey

Table 4.1: Respondent characteristics for free text responses (n=33)

Sex	**Number**	**(%)**
Male	18	55
Female	14	42
Not provided	1	3
Age group		
20-29	5	15
30-39	8	24
40-49	10	30
50-59	7	21
60+	0	0
Not provided	3	9

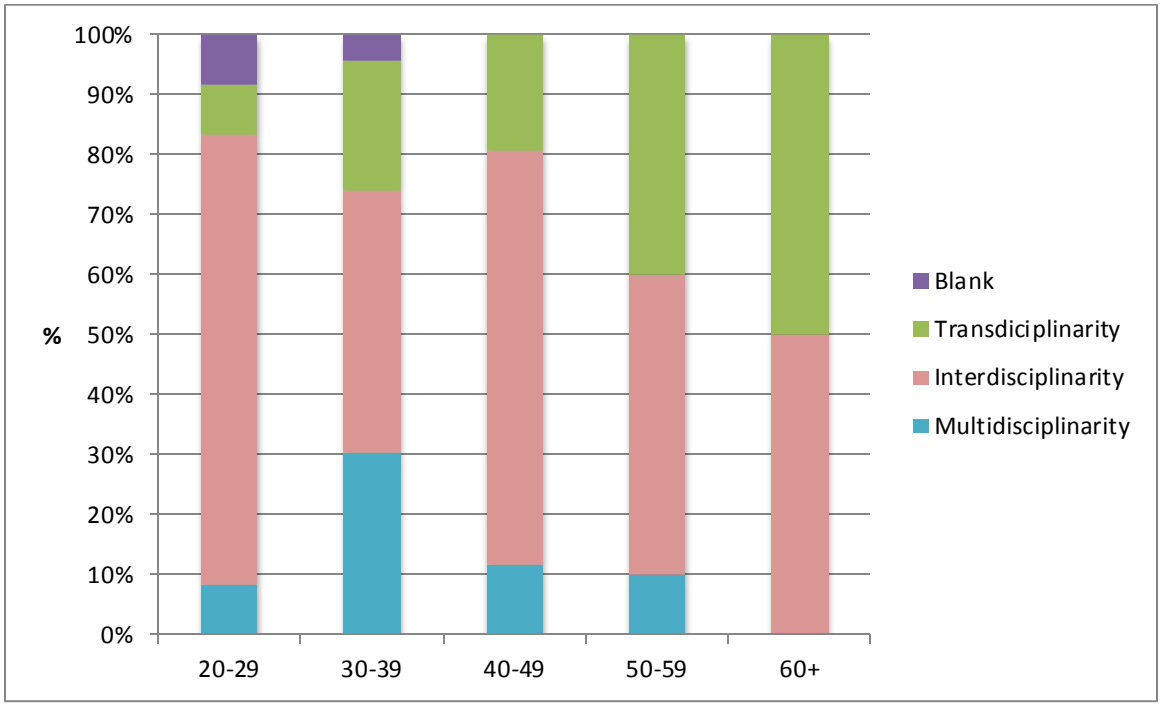
Note: % do not sum to 100 due to rounding

Annex 5: Assessing association between selected variables

Overall, there is no pattern of association between independent variables such as age, gender, and the time worked at the Institute with dependent variables such as how respondents understand interdisciplinarity, the level of experience of interdisciplinary working, whether they combined social and natural science approaches, and what proportion of the work carried out is of an interdisciplinary nature. This annex reports selected findings.

1. Age and definition of interdisciplinarity

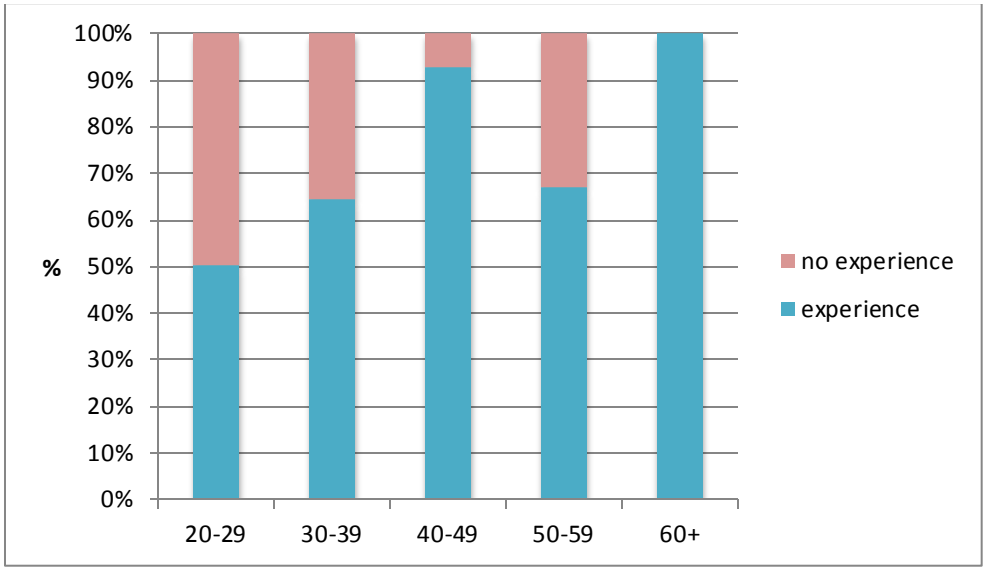
Definition of interdisciplinarity (according to explanation in section 4.3)



- In the age group under 39 respondents gave blank responses.
- The highest proportion of respondents with an understanding of IDR that matched Tress *et al*.'s (2004) definition of interdisciplinarity was found in the age group 20-29.
- The age group 60+ does not consider multidisciplinarity as an option (but note there were only two responses in this age group).

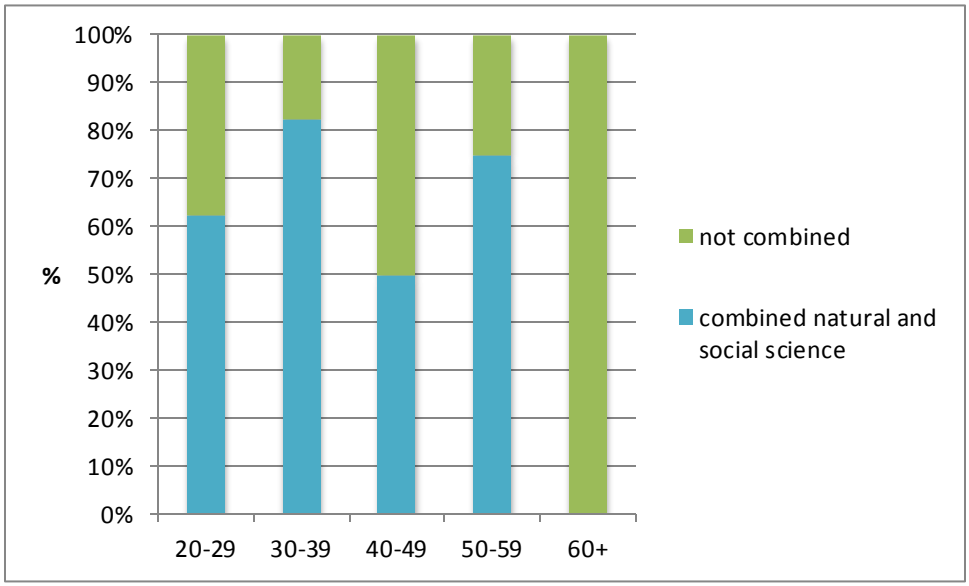
2. Age and experience of interdisciplinary projects

All respondents from the age group 60+ reported experience in interdisciplinary projects, while a half-half split is found for 20-29 years old. Inferences would need to be carefully made given the unbalanced representativity of each of the groups (e.g., 2 only in 60+).



3. Age and experience in projects combining natural and social sciences

Of those respondents that reported having worked on IDR projects, a majority had combined natural and social sciences in those projects. The age group 60+ is an exception; here respondents had not combined social and natural sciences.



4. Age and proportion of interdisciplinary work at present

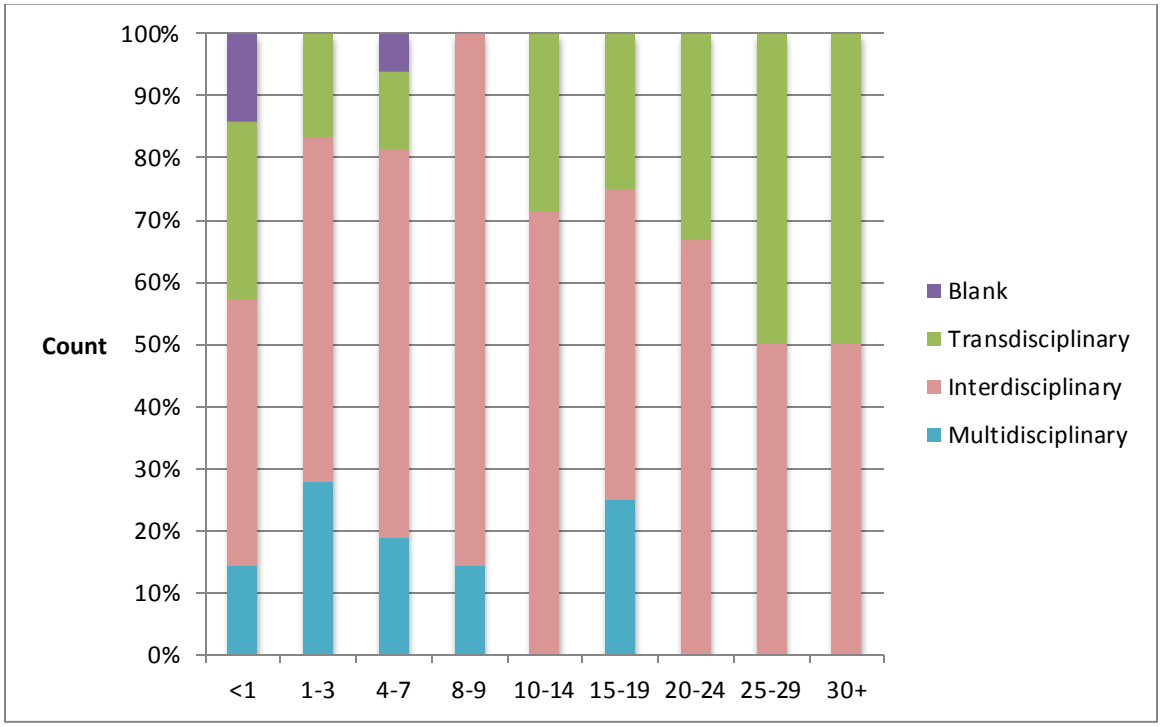
No strong relationship or clear pattern could be found

5. Time worked at the Institute and definition of IDR

- In the group of respondents who have worked at the Institute less than 7 years there are blank responses.

- For respondents who have worked at the Institute under 19 years, there are cases of having an understanding of interdisciplinarity that matched Tress *et al.*'s (2004) definition of multidisciplinarity.
- Respondents in the group that has worked for more than 20 years at the JHI selected either the inter- or the transdisciplinary definitions

Time worked at the Institute	Multi-disciplinary	Inter-disciplinary	Trans-disciplinary	Blank	Total
<1	2	6	4	2	14
1-3	5	10	3	0	18
4-7	3	10	2	1	16
8-9	1	6	0	0	7
10-14	0	5	2	0	7
15-19	1	2	1	0	4
20.24	0	4	2	0	6
25-29	0	1	1	0	2
30+	0	1	1	0	2
Total	12	45	16	3	76

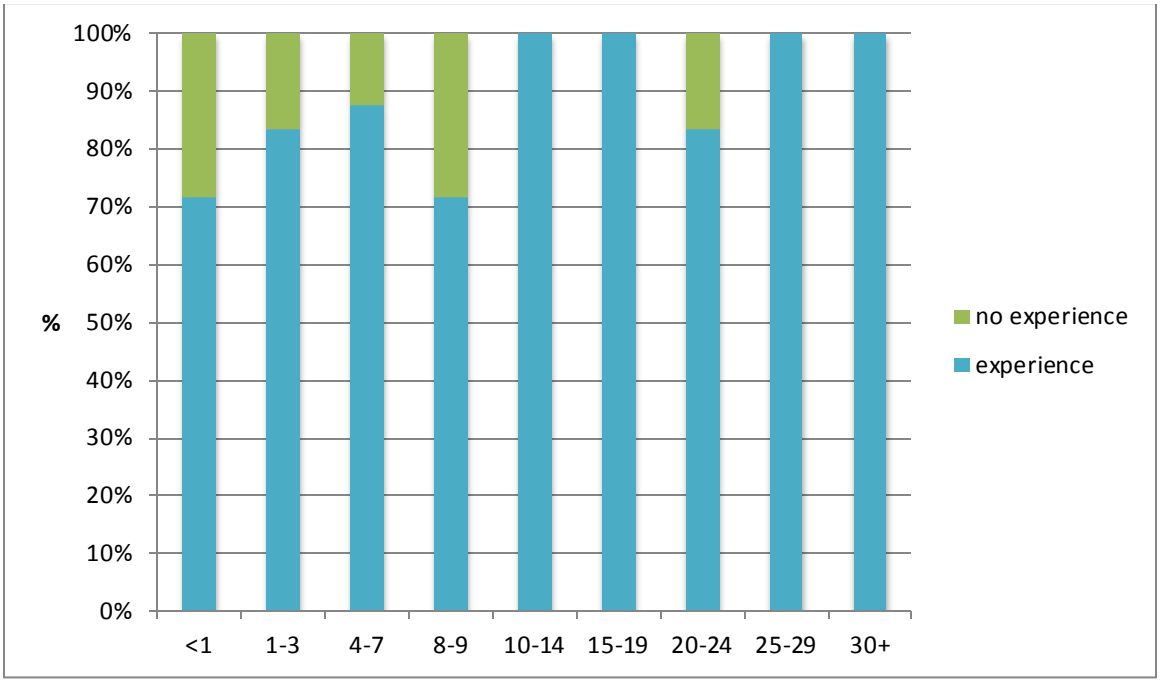


6. Time worked at the Institute and experience of IDR

- There appears to be a trend of more experience with IDR in those groups that have worked at the Institute longer.

Q2	Experience	No experience	Total
<1	10	4	14
1-3	15	3	18
4-7	14	2	16

8-9	5	2	7
10-14	7	0	7
15-19	4	0	4
20.24	5	1	6
25-29	2	0	2
30+	2	0	2
Total	64	12	76



7. Gender

Gender had no influence on interdisciplinary working. Using Fisher´s exact test, no association between gender and the following variables could be established:

- experience working on interdisciplinary projects (81.6% of the males and 85.7% of the females)
- reporting projects that combined natural and social science (47.4% of the males and 54.3% of the females)
- Proportion of work with an interdisciplinary nature
- Change over time in the extent of involvement in interdisciplinary research

Annex 6: Conceptual framework for the literature review