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ABSTRACT Although both research funders and knowledge users continue to call for more and higher-quality collaboration between researchers from different disciplines, there is little evidence available to inform the structure and management of cross-disciplinary research teams. A descriptive account of cross-disciplinary collaboration is presented based on a study of a cross-disciplinary team researching natural resource degradation issues. A number of tools are identified that characterize and support the collaboration process, including the use of story-lines and metaphor, choice of vocabulary, the nature of dialogue and the role of mediating agents. Four products of collaboration are also identified: 'process', 'understanding', 'utility' and 'knowledge integration'. Conclusions focus on the implications for research programme design and the content of research training curricula.

Keywords collaboration, cross-disciplinary research, research management, research teams

Smoothing the Waters: Observations on the Process of Cross- Disciplinary Research Collaboration

Paul Jeffrey

It has been said variously that Aristotle, Leibniz, John Stuart Mill and Thorstein Veblen was the last human being to have known everything. Irrespective of the accuracy or indeed the significance of these claims, the anecdote does emphasize the increasing breadth and depth of scientific knowledge that has resulted in the emergence of a myriad of disciplines or branches of learning, each one requiring many years' study to reach the forefront of research. This ever increasing specialization has prompted many to consider how disparate scientific contributions can be rebuilt or integrated to provide solutions to (or at least help us understand) the complex challenges which face our communities. Such cross-disciplinary research is now almost 'de rigueur', even though we remain largely ignorant of the determinants of good practice, or the effective translation of its output into policy and decision support tools.

A central motivation for research funders to support studies that consider the contributions of more than one disciplinary field is the fact that real-world problems do not come in disciplinary-shaped boxes. Indeed, national research policies lay increasing emphasis on problem-oriented research, which requires the crossing of disciplinary boundaries

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(Weingart & Stehr, 2000). Clearly, the complexity and sheer magnitude of information and knowledge emerging from interdisciplinary research activities need structuring, and the linkages between the various contributions identifying, if the full utility of such studies is to be enjoyed. Consideration of this problem in theoretical terms (Reiser, 1958) has largely given way to investigations of the practical problems involved. Other writers have highlighted the significant role played by communication in cross-disciplinary teams (Berkenkotter & Ravotas, 1997; Wear, 1999), the motivations of researchers who engage in collaboration (Melin, 2000), and the influence of group dynamics on individual and team performance (McCorcle, 1982; Johnson & Johnson, 2000).

Although interdisciplinary research has become fashionable amongst both funders and practitioners, its methodological development has been constrained by the knowledge base being itself dispersed amongst a variety of disciplines. There remain significant difficulties in turning cooperation (working together for individual ends) into collaboration (working together for a common end). Ambiguous use of terms by single-discipline scholars and a dearth of progressive writing on interdisciplinarity as a subject have resulted in little substantive progress being made in providing integrated, cross-disciplinary assessments of the challenges which face our communities.¹ In particular, science as a problem-solving method has failed to make a distinction between contributions that are simply edited summaries of a sequence of isolated research activities, and contributions which provide genuine integration through collaborative working and common methodological frameworks.

The term we adopt here for all forms of collaboration between researchers with different educational backgrounds is 'cross-disciplinary'. Rossini & Porter (1984) propose a three-way classification of cross-disciplinary studies. They see 'Multidisciplinary Research' as comprising a number of independently performed studies with external coordination through appropriate editorial linkages. 'Transdisciplinary Research' is considered to include the development of an overarching paradigm that encompasses a number of disciplines and (latterly) stakeholder groups. Finally, 'Interdisciplinary Research' falls between the two previous approaches: components being linked internally and substantively without being subsumed under a supradisciplinary paradigm.

Recent writings by the group of theorists centred on Michael Gibbons (for example, see Gibbons et al. [1994] and Nowotny et al. [2001]) have provided the transdisciplinary paradigm with a socially significant function. They suggest a radical reform of the organization of science, moving from work that is defined in relation to the cognitive and social norms that govern academic science, to knowledge produced in the context of application. So, instead of producing knowledge within the discipline, research teams become transdisciplinary and heterogeneous. Reactions to this analysis have claimed that the changes described are neither distinctive nor historically unique. Furthermore, critiques of the implications for science

have shown how our understanding of interdisciplinarity is very closely tied to epistemological assumptions about the relationship between science and nature, and the structure of science and scientific disciplines (Weingart, 1997). The debate has fuelled calls for a greater degree of collaboration across the science–society boundary as well as across disciplinary boundaries (Klein et al., 2001: 7).

Locating the material reported later within a broader intellectual tradition is problematic.² The literature on cross-disciplinary interaction is fractured by competing explanations focused on theory, praxis, language, understanding and action. This contribution does not aid clarification or simplification of these contending descriptions (although we will briefly discuss their salient points as they pertain to observed processes). However, through monitoring and analysing the process and experience of collaboration we feel that we have some valuable comments to offer concerning the relationships between inquiry frameworks and research method. There are, as yet, few case studies available that can provide evidence-based, prescriptive guidance for research managers at both project and programme levels. Such studies are a simple yet essential step towards greater understanding of cross-disciplinary research processes.

Method

The evidential material upon which the findings and conclusions of the present paper are based was collected during an 8-month period, during which the investigator was asked to act as intermediary for, and report on, the process of interaction within a cross-disciplinary research team. The research team were working on a project funded by the European Commission that focused on exploring the determinants of, and responses to, desertification processes in Southern Europe. In particular, a sub-group of the research team was asked to prepare a micro-simulation model of crop-choice dynamics in a case study area of Southern Greece. This group initially consisted of 10 researchers from a variety of disciplinary backgrounds: sociology, agronomy, anthropology, archaeology, biology, simulation modelling and computer science. However, during the initial phases of the project, the team became polarized into two factions: social scientists and simulation modellers. The intermediary had a background in ‘Science and Society’ and ‘Socio-Natural Systems’ and was of a relatively junior academic status, but had worked previously with several of the research team (both modellers and non-modellers). Primary data on interactions between the researchers were collected through observation and annotated records of the collaborative working meetings (42 h) and two interviews with each of the 10 members of the team (one mid-way through the project and the other on completion). This model of primary data acquisition clearly has restrictions, although it has been used effectively both in isolation and as part of multi-method approaches in previous studies of this type (for example, see Anderson [1992] and Newell & Swan [2000]).

The micro-simulation model developed by the project described a multi-function assessment of various economic, technological and environmental constraints affecting farmers' choice of crop. Decisions regarding changes in agricultural land usage have an immediate and widespread influence not only on the physical and chemical properties of the soil, but also on its relative productivity. The simulation algorithm used in the model was based on the use of a probability density function in 13 dimensions that governs crop-choice behaviour on a theoretical representation of the farming landscape. Social enquiry data (from surveys and studies carried out by the social scientists) were to be used to characterize the behaviour of the transition matrix: for example, what motivated farmers to change crop, modify agricultural practices, or indeed, get out of farming altogether.

Both sets of researchers agreed that a representation of the farmers' cognitive process when deciding on crop change constituted the focus of effort. In other terms, the cognitive background and contextual determinants of crop-change decision-making were to be preferred over an approach that emphasized the process of coming to a judgment on crop selection. Hence the activity could be defined as one whereby the knowledge of farmers' attitudes and behaviour, as monitored by researchers in the field, is elicited from the social scientists and formally structured in a format that enables it to be included in a computer-based simulation model.

As noted earlier, relationships between the disciplines were informally monitored during the project, with the aim of developing a critique of the interaction between the various disciplinary representatives. In particular, attention was focused on areas where common understanding was restricted and where genuine integration of knowledge proved difficult to achieve. The intellectual dynamics between the various groups of researchers (as reported later) has implications both for disciplines in isolation and for interdisciplinary research as a whole. Whilst it might be ill-advised to term the relationship between the various traditions involved in the project as 'synergetic', a circumspect observer might point out the essentially dialectical nature of the discourse and label it 'mutually informative'.

Structuring a commentary on the nature and significance of collaboration between different scientific disciplines calls for a frame of reference. Without a framework within which to comment on the observed interaction, this text would be in the format of reportage, simply describing the sequence of events without identifying their relevance. The task is therefore to select an appropriate frame of reference or thematic structure that can be used to interpret the observations. Several candidates for such a structure are available from other academic fields. For example, the study of organizations could be considered as an appropriate starting point, as cross-disciplinary collaboration involves similar types of process. The same could be said of group dynamics and some branches of education theory. However, the types of individuals involved, and the nature of the activities taking place, are significantly different in the case of cross-disciplinary

collaboration. In addition, we are seeking a framework that will allow us to look beyond issues of control, personal interaction and decision-making, to identify areas of collaborative success/failure as perceived by both an observer and the members of the research team themselves. Because we would like to involve the research team in a debate about collaboration, the way in which we describe its constituent elements also needs to be readily comprehended and understood. Consequently, there is a need for a measure of simplicity and transparency for any thematic structure we might adopt.

The precise thematic structure selected for use in the present paper is therefore intentionally straightforward and uncomplicated, highlighting the means by which collaboration is accomplished (tools) and the outcomes of collaboration (products). Conversations with members of the research team about collaboration across the disciplines were typically focused on the means and output of collaboration, indicating that these are topics of concern and significance to the collaborators themselves. Hence, using a thematic framework that highlights the tools and products of collaboration has relevance to the project team and is also of sufficient scope to allow a broader discussion of the more abstract features of collaborative activities.

In detail, four products are identified, each one representing a specific feature of the collaborative process. These products are denoted as 'process', 'understanding', 'utility' and 'knowledge integration'. Tools of collaboration are devices and mechanisms that are utilized to achieve these products. Relevant tools include the use of 'story-lines' and 'metaphor', the choice of 'vocabulary', the nature of 'dialogue' (in this case, negotiation) and the role of 'mediating agents'. This is clearly not an exhaustive listing of relevant tools and products. However, the specifics of the disciplinary interactions observed over the 8 months of the study suggest that the tools and products itemized provide a sufficiently rich framework within which to discuss the issue of interdisciplinary collaboration. The relationship between tools and products is hierarchical: the tools of collaboration can be seen as conduits for the achievement of products. Furthermore, it is important to note that by discussing cross-disciplinary collaboration in terms of tools and products, we do not seek to propose a formal theoretical structure for analysing the process. Indeed, if there is a theoretical contribution contained in this paper, it is in the disaggregation of collaboration into component elements (products).³

The Collaborative Process

As noted earlier, the task objective for the collaborating team was to produce a simulation-based crop-change model based on primary data of farmer decision-making considerations. In particular, issues of time scale (how often farmers make a decision about, for example, irrigation), the options for change and the influences these changes may have, were considered of immediate significance. Although an initial attempt was

made to use diagramming to support interaction between the two groups, the discussion soon became disjointed and unfocused. The primary reason for this was that the variety of behaviours and decision-making criteria that the social scientists had recorded in the field confounded attempts at a structured, simplified formulation. It is worth noting that this temporary breakdown in effective communication between the modellers and social scientists (despite the efforts of both sides to maintain a constructive dialogue) was unrepresentative of the relationship as a whole. It did, however, have a secondary effect as part of a process that saw a reduction in the number of disciplinary representatives actively engaged in this element of the project. Although logistical (location) and resource (funding) constraints were also contributing factors, it was evident that this early impasse in the production of a common vision for the work led several researchers to withdraw from the process.

Perhaps sensing that the framework used for eliciting data for the model needed to reflect some kind of formal decision-making structure, both sides moved towards an approach that involved breaking the decision down into a number of components. A series of sub-system diagrams were sketched, each of which related to a distinct decision issue: for example, the decision to irrigate, the decision to pump water, the decision to operate a windmill (as protection against frost), the decision to add fertilizer. By using these cause–decision–effect tables, a series of decision trees could be formulated, each one relating to a specific decision issue. The link between the decision trees and the modelling activity is clear. The structure and format of the decision tree is readily coded as a sequence of ‘IF’ and ‘AND’ rules.

Structuring a set of decision trees in this way was not considered to be technically demanding. However, two aspects of the approach caused disquiet amongst the social scientists. First, any single representation constituted a unique mode of behaviour. Although the modellers explained their intention to instil diversity of behaviour by applying ‘noise’ to the process, the social scientists were concerned that the qualitative nature of variety would not be captured. In particular, there was a feeling that a data-driven representation of the mechanisms that generate variety of behaviour was required rather than a numerical simulation of the variance. Second, although the approach provided opportunities for the crop change element of the model to be integrated with the physical (soil, climate) and economic elements, the range of variables being considered was unrealistic. In the words of one of the social scientists, ‘Farmers just do not go through that thought process every time they want to irrigate their land’. In an attempt to structure the decision issue in a more formalized manner, the level of abstraction had become too far removed from what the social scientists regarded as being acceptable.

During a discussion of the details of the computer model itself, it was suggested and agreed that a possible alternative structuring technique was to use a transition matrix. Completion of the cells within the matrix involved the social scientists considering each cell of the matrix in turn,

and determining an appropriate value between 0 and 1 (representing the possibility of crop change). However, the sheer size of the task and the often detailed considerations that were involved in coming to a determination of the probability of crop change made the activity difficult to manage and impractical. Whilst some attempt was made to make progress, it soon became evident that the social scientists found it difficult to maintain a consistent focus on the determinants of crop change and that the set of four bi-modal descriptors being used (Farmer type – full time/part time; Soil quality – good/bad; Location – central/periphery; Irrigation available – yes/no) did not even begin to capture the context of, or influence on, each possible crop-change event.

On reflection, the central dynamic of these attempts to formalize the crop-change decision was focused on pinning down the appropriate level of variety for inclusion in the model. A caveat to this goal was the concern that elicitation of the information (in whatever format) had to be a manageable, understandable and achievable process. In another, more uncompromising sense, the debate concerned the representation of variety and, perhaps more significantly, responsibility for handling variety. The computer modellers often spoke of introducing ‘noise’ into the system without clearly explaining the mechanism by which they intended to achieve it. They also continued to emphasize the point that variety could be built into the model at a later stage, following resolution of the model’s structure and identification of key variables/relationships. Similarly, the social scientists spoke of the difficulties and dangers associated with standardizing the representation of behaviour. Simply by the act of verbalizing a specific mode of behaviour, they committed themselves to a representation that they knew was possibly unique and ungeneralizable.

Two distinct, and contrasting, methodological systems are evident here. The very nature of computer simulation imposes a structure on both the type of analysis and information that are to be used. Analysis routines must be sequential and transparent (every event must have an identifiable precursor). Data must be ordered and classified. In contrast, the knowledge possessed by the social scientists (concerning farmers’ perceptions of crop change) suggests at best a semi-structured process. The decision process, if there is one, is opaque and the contributing considerations are often confused and variable across individuals. A valuable observation in this context (made by one of the social scientists) was: ‘Will the nature of the variety that the modelling activity achieves match that observed by the social scientists in the field?’

The desire of both sets of researchers to make progress on the project, and the appreciation that what was being attempted constituted a non-trivial activity, encouraged a pragmatic approach to the work. However, there remained an underlying sense of scepticism (bordering at times on suspicion) from the social scientists in particular, regarding the representational aspects of the proposed computer model. For example, just how much variety could be built into the model as ‘noise’ and how much could be handled at the level of formal rules and transition functions was an

ongoing topic of concern: the social scientists feeling their way towards a representation that exhibited some structural correspondence with the farmers' (assumed) cognitive constructs. In addition, there was a feeling amongst the social scientists that the variables that had been selected for inclusion in the activities to date had been arrived at arbitrarily. For example, the four bi-modal descriptors highlighted earlier were chosen without any obvious defence for their preference over others.

At this point, a consensus began to emerge within the group of social scientists for a hybrid approach to the structuring of the crop-change model based on the concept of multiple filters. These would be in the form of two sets of templates overlying a geographical map of the region. The first set of templates would indicate the physical, chemical and hydrological limitations to crop choice (that is, what you can and cannot grow on a plot). The second set would indicate farmer-specific considerations such as cost, technology access and labour availability. The various templates would then be used to generate a dynamic model of crop choice with interactions between the physical, economic and other variables. In effect, such an approach passes on responsibility for the handling of variety to the computer modellers. It allows the social scientists to concentrate on a broadly applicable structure for the crop-change decision issue and the identification of the relationships between the contributing factors as perceived by the farmer. The preferred technique with which to capture the farmers' perception of the decision issue was to apply an adapted version of the decision-tree approach. The decision-tree structure was to be driven by interview data and representations of variability were to be based on farmers' stated biases. The aim here was to derive a representation of the farmer's consideration of the issue by identifying both its constituent elements and the relationships between them. The term 'constituent elements' infers those aspects of the decision issue that are considered by the farmer. For example, in the case of the crop-change decision, relevant factors might include the suitability of the soil, the existence of a potential market for the crop and expected income levels.

This broadly supported approach to capturing illustrative crop-change decisions represents a compromise between the uncoordinated demands of the two sets of researchers (modellers and social scientists). Perhaps it would be more accurate to say that it allows two incongruous approaches to be 'reconciled' rather than 'integrated'. The problem, as throughout the process, was one of capturing variety. It was impractical to collect data that would enable each farmer on the landscape to be represented as an individual, or to code all the farmers as individual agents within a simulation tool. However, it was also undesirable to simply apply a stochastic function to represent the distribution of behaviour amongst farmers. Hence, some middle ground needed to be found which allowed diversity of perception and subsequent behaviour to be represented in a format that was both authentic and pragmatic. By using the notion of a 'prototypical farmer' as the basis for representing a hierarchical and relational structure

for the decision issue, the collaborators were able to achieve a standard format but maintain the potential for the representation of variety.

Results from the Study

Before relating the details of the study's findings in terms of the tools and products of collaboration, it is worth outlining two issues that dominated discussions within the cross-disciplinary group. The first of these issues concerns the divergent preferences for a representational structure in the model. From the computer modellers' viewpoint, the decision as to which mechanism to adopt for representing the farmers' decision framework was purely a function of whether the relevant processes could be structured and quantified (although this raises its own problems as will be discussed later). Conversely, the social scientists' desire to present a 'true' picture of the farmers' cognitive processes made them implicitly favour a decision-tree approach over a transition-matrix approach. Second, the intended function of the computer model and the consequences of this for the type of information required from the social scientists emerged as central areas of misunderstanding. Those working on the modelling side of the project were keen to emphasize the distinction between bounding the *actual* and bounding the *possible*. In context, the distinction here is between developing a model that faithfully represents the farmers as they behave with regard to crop choice now, and developing a tool with which we can explore the opportunities and options that might be open to the farmers, and implying from those trajectories a set of policy implications. This distinction is an integral part of iterative approaches to modelling, where model design is initially of an elementary and uncomplicated nature, complexity and detail emerging from iterative development of the model's structure and dynamics. In addition, given the role of the model as an exploratory tool for investigating the dynamics of change in the case study region, some indication of what is possible clearly determines the bounds of behaviour. From the practical viewpoint of achieving some progress in melding the knowledge of the social scientists with the intentions of the computer modellers, the distinction between actual and possible behaviour provided an ongoing source of diversion.

We now turn to a discussion of those tools (vocabulary, metaphor, story-lines, negotiation, role of intermediary) that were identified as being fundamental to the achievement of the products of collaboration (process, understanding, utility and knowledge integration). A brief summary of the products themselves will then be provided.

The Role of Vocabulary

Vocabulary refers to the words that we use to communicate the meaning of our thoughts. The variability of experience and learning, and the magnitude of available expressions generate a myriad of possible vocabularies. Science and scientists, driven by the need to distinguish, define and describe, are infamous for developing new vocabularies. It is not surprising,

therefore, that when representatives from two different scientific disciplines meet, they have difficulty making themselves understood. Ideas generated within one discipline may make perfect sense within the discourse that they came from. However, they will be evaluated in the context of acts and practices that do not function according to the discursive logic of the original discourse. Hence, even though the representatives of different disciplines may be discussing a single, unambiguous topic, their vocabularies may be very different and mutually perplexing.

It can be appreciated that collaboration between the disciplines is hampered by the absence of a collective and comprehensible set of reference terms. Indeed, one of the most significant processes observed during the development of the micro-simulation model was the evolution of a common vocabulary. Propelled by the use of simile, analogy and metaphor, this shared language set was, in fact, an integrated version of the individual vocabularies used by each group. Both the social scientists and the modellers adopted words, terms and phrases from each other's vocabularies with varying levels of success. Interestingly, the meanings of certain terms and phrases were subtly altered as they moved across from a discipline-specific to a common vocabulary, creating a small collection of terms that had an interpretation unique to the cross-disciplinary activity itself.

The evolution of a common vocabulary was observed as being influenced by several factors:

- Size of group – as the collaboration progressed and the size of the contact group diminished, so the rate at which a common vocabulary developed, increased.
- Presence of an intermediary – the intermediary who worked as part of the contact group had previously worked on both social science and modelling-related projects and was able to facilitate the development of a common vocabulary.
- Listening – a willingness to ‘shut up and listen’⁴ clearly allows other actors to articulate a point and introduce possibly useful words into the common vocabulary.
- Dedicated and focused working sessions – these limited the amount of ‘noise’ that tended to accompany cross-disciplinary interaction.
- Discussion about the use of the model as well as the design of the model – providing opportunities for individuals to extrapolate their understanding of the model from setting the structure to manipulating its functionality, allowed the emerging common vocabulary to be placed in a relevant context.
- Use of diagrammatic representation – the use of drawings, graphs, sketches and other pictorial representations helped to clarify disputed or unclear descriptions.
- Respect for the limitations of one's own and others' understandings – despite its critical role, this is a somewhat difficult factor to capture in terms of specific actions. A willingness to explain things from first

principles if need be, and an openness about one's own ignorance are, however, cornerstones of an ongoing and productive cross-disciplinary relationship.

Perhaps surprisingly, the development of a common language set was not observed to be a significant hurdle to cross-disciplinary collaboration. Individuals from both the modelling and social-enquiry groups prompted their colleagues to clarify words and phrases with which they were unfamiliar. Although this process of developing a mutually comprehensible vocabulary slowed down the pace and often interrupted the flow of discussion, it became a decreasing burden on dialogue and eventually ceased to be a significant hindrance. It should also be noted that the emergence of a mutual vocabulary and its use as a catalyst for collaboration can be cited as a positive contribution to the project's aims.

One final general observation should be made here concerning this element of the interaction. The task of explaining and clarifying misunderstood terms was carried out within an informal communicative structure that progressed from verbal definition, through verbal example to non-verbal representation. Most queries were dealt with simply by providing a spoken, formalized definition of the term or phrase. In the event that this was not sufficient, recourse was made to examples, comparisons and analogies. Finally, if misunderstanding persisted, diagrammatic or pictorial techniques were used, and the help of other contact group members was solicited.

The Role of Metaphor

The significance of metaphor in linguistics is already well established, and there is a long-standing and detailed literature concerning its use as an aid to understanding and thought.⁵ However, within the context of collaboration between scientific disciplines there are a number of issues which were found to be of particular interest.

Information flow between the two disciplines involved in the micro-simulation model development (and the subsequent need for understanding) occurred in two distinct phases. Through dialogue, there was a continual flow of information in both directions. Initially, however, there was a bias in the need for understanding as the modellers struggled to formulate a structure for the model that matched the nature and availability of the data. Later in the study, the bias was reversed as it became important for the social scientists to understand what the model was and was not capable of representing. Metaphors were exploited extensively by both groups during these processes. Interestingly, the use of metaphor was discernible as a tool for both explanation and query, and 'dominant metaphors' were referred back to when actors felt that they were losing the clarity of an explanation.

The term 'dominant metaphor' indicates a metaphor used on numerous occasions to illustrate different points. Such metaphors were incrementally developed over the course of several encounters, gradually

increasing in complexity and yet becoming less abstract and closer to a full description of the source phenomena. Clearly, as some metaphors became dominant, so the integrity of understanding between the disciplines became dependent on a few, core analogies. This trend did not appear to be detrimental to continued and growing understanding, although it did have the effect of bounding the range of communication tools available.

Metaphor usage amongst the contact group was also highly explicit. References to analogous or similar phenomena to those being discussed were prefixed or suffixed with a clear indication that metaphorical language was being used. For example the expression 'you can imagine the template as a sort of filter through which only certain things pass' would be typical of this style of metaphor use. The terms '*sort of*' and '*imagine*' make it clear that a substitute for the real thing is being referred to. Having encountered similar approaches to explanation during their education, such measured use of metaphor may well be a characteristic of academics in general.

Finally, it was observed that all parties succumbed at various times to using easily understood but otherwise inappropriate metaphors. These were often simple analogies, possibly even single words, the possible misunderstanding of which had not been considered.

The Role of Story-Lines

The role of story-lines in promoting understanding has only been raised relatively recently in the literature. They have been described as a 'generative sort of narrative that allows actors to draw upon various discursive categories to give meaning to specific physical or social phenomena' (Hajer, 1996: 56). With reference to the issue of collaboration between the disciplines, the observed interaction during the study provided evidential support for the following features of story-lines.

- They have the functional role of facilitating the reduction of the discursive complexity of a problem and creating possibilities for problem closure.
- As story-lines are accepted (more and more actors start to use them), they get a ritual character and give a certain permanence to the debate.
- They allow different actors to expand their own understanding and discursive competence of the phenomena beyond their own discourse.
- They provide a narrative that allows actors from different disciplines to illustrate where his or her work fits into the jigsaw.

Hence, story-lines provide actors with a set of symbolic references (expressed through language) that suggest a common understanding. Indeed, some authors have interpreted the phenomenon of story-lines as having a central contribution to make towards collaboration in its broadest sense. They see them as fulfilling 'an essential role in the clustering of

knowledge, the positioning of actors, and ultimately in the creation of coalitions amongst the actors of a given domain' (Hajer, 1996: 63).

Although most of the theoretical work on the use of story-lines has been carried out in relation to the fields of policy studies and politics, there are significant areas of application to the understanding and promotion of cross-disciplinary collaboration. For example, whilst there is little relevance in the policy-focused process whereby story-lines promote a discursive coalition, the disciplinary actors involved in the micro-simulation study all needed to both understand and be able to articulate (express either verbally or with diagrams/text during discourse) the same data structures. Hence, there is a commonality of welfare in both cases. Furthermore, the use of certain vocabularies (and more significantly of metaphor *per se*) in cross-disciplinary discourse bestows a pseudo policy-related language set on the interaction. Actors use abstract and conceptual images akin to those typical of policy-level debates.

The Role of an Intermediary

We would make two points regarding prerequisites for the successful functioning of an intermediary. First, it is dependent on an acceptance by all parties of the mediator's integrity and good will. The disciplinary groups need to believe that the intermediary is a credible and competent individual, and that he or she has the best interests of the project as a whole at heart. Second, an intermediary needs to be able to communicate effectively with all concerned parties. Experience of operating intellectually in more than one disciplinary area is therefore desirable, as is some knowledge of cross-disciplinary knowledge integration issues.

During the project, an intermediary was able to facilitate the process of collaboration by:

- Maintaining a focus on the collaborative aspects of the study. Cross-disciplinary collaboration was permanently at the top of the intermediary's agenda.
- Being able to force an issue without damaging the relationship between the disciplines. If progress was being held up, the intermediary could take a difficult or potentially unpopular decision. Any resultant antagonism or enmity would be focused on the intermediary and not on other members of the contact group.
- Assessing the relevance and value of suggested activities. Through having experience of both disciplines, the intermediary was able to identify potentially counter-productive methodological or technical initiatives.
- Assisting in the development of a common vocabulary and interpreting the use of metaphor (see earlier).

In addition to these generally constructive components, there were a number of negative aspects that were also identified. The most significant

of these was that the intermediary is prone to being drawn into the collaborative exercise as an actor (for example, *performing* a data interpretation exercise rather than *facilitating* data interpretation).

The Role of Negotiation

It would be deceptive to claim that negotiation was an intended element of collaboration in this study. Indeed, we can only denote the nature of the observed dialogue as 'negotiation' in retrospect (apart from in one specific case which is dealt with at the end of this section). Having carried out a limited 'debriefing' of the researchers involved in the study, we find that there has been a strong perception on their behalf that the model's structure and content have been negotiated between the social scientists, modellers and intermediary. We would point out that whilst negotiation may not be the only or the best form of dialogue between the disciplines, it was the dominant form here as perceived by the participants.

Negotiation is a search for agreement, often through a process of 'give and take', where each side relinquishes some ground on one issue in exchange for gaining ground on other issues. That the nature of model development should be described in this way may initially appear both unusual and inappropriate. However, given the intellectual backgrounds of the two disciplines concerned, the emergence of an essentially dialectic process is not surprising. Although the relative effectiveness of negotiation as a form of interaction in this case is difficult to assess, there are several dimensions of the process that we would highlight at this stage.

First, negotiation promoted the development of a *plausible* model. Frank and open discussion of each participant's own impression of the model's form and content resulted in consensus regarding what was feasible and achievable within the timescales available. Achieving such consensus often involved team members bounding the intentions or expectations of others (for example, by drawing attention to the limitations of data sets or modelling techniques). Second, negotiation promoted a particular form of verbal interaction that tended towards debate as opposed to discussion. Interaction was driven by relevant issues or problems. Participants had distinct positions on these issues which they stated early on, inviting others to do likewise, leading to the essentially dialectic process alluded to earlier. Finally, the negotiated form of interaction created its own dynamic by maintaining contact between participants where it might otherwise have collapsed. Because the final act of negotiation is agreement, there was little opportunity for one party to withdraw completely from the process. Dialogue continued even when consensus was elusive.

As noted earlier, there was one aspect of the cross-disciplinary interaction that could clearly be identified as 'negotiation' during the study itself; the desire by both sides (sociologists and modellers) to negotiate responsibility for complexity. The data set collected by the social scientists contained a large amount of information, both in terms of the number of

attributes and the types of links between attributes. A relevant and complex story-line (see earlier) had already been formulated describing the perceptions recorded during the survey work. Capturing and representing the complexity of farmer perceptions and behaviour was an agreed objective. How this was to be achieved was less clear and became an issue that was sporadically and indirectly negotiated during the early stages of model development.⁶

Negotiation as a dominant discursive style between the disciplines was also evident in the later stages of the project, particularly during project reporting. As noted later, several different collaborative composition styles were evident, each one providing opportunity for negotiating the content and structure of the final product. Where interaction was at the level of the statement, negotiation tended to focus on the factual consistency and meaning of the text. Contrastingly, where interaction was at the thematic level, negotiation was concerned with the synergy between the various contributions. If comparative utility is to be allocated to these two collaborative writing styles, then practical collaboration at the thematic level appears to hold more potential for exploitation.

Having discussed the tools of collaboration, we now move on to address the products of cross-disciplinary collaboration. These outcomes are proposed as a non-exhaustive catalogue of benefits emergent from the particular research process discussed earlier. They are necessarily abstract in as much as they attempt to classify a typology of outcomes within which more specific achievements may be realized.

Collaboration Between the Disciplines as Process

Collaboration as process is simply the ways of working together. Its constituent elements are contact, interaction, and communication. The significance of process as a product is strongly associated with the notion of action and response. Process is maintained by an open and constantly maturing agenda, the development of which is supported by dialogue between the disciplines. With regard to assessing the value of process, it is difficult to judge collaboration as process as successful or unproductive independent of the success of other, related products. However, as we are concerned here with a specific collaborative endeavour, some indicators by which we may begin to assess the constructive aspects of collaboration as process can be suggested.

As a starting point, we may address the activities of the contact group itself. The central dynamic that dictated the process of collaboration between the modellers and sociologists evidently was the evolution of the contact group. In terms of the number of people involved, the group started with 10 members and completed its task with a core of just 3. In terms of activities, the first contacts were in the form of formal, scheduled meetings that gave way to informal visits between sites. Finally, the frequency of interaction between members of the group increased as the

project advanced. Hence the nature of process changed as a reflection of the evolving interactions between individuals. But why change the nature of the process? How did the group interactions evolve in this way ... by serendipity or design?

A partial response to this query is that it was just the way things happened. Viewing the events in slightly more detail though, we can pinpoint some of the reasons why the changes occurred. For example, group size (the numbers of people actively engaged in the contact group) became reduced in the latter stages of the project due largely to the fact that as the model specification began to be narrowed down, fewer individuals were able to contribute in a constructive way. As the contact group became smaller, informal modes of meeting and communicating became the norm and the individuals involved got to know each other on a personal basis. This informality was also reflected in the way progress was measured. An explicit timetable linking specific activities with progress was not evident at any time during the simulation project. Progress was informally measured in terms of the relationship between assumed workload remaining and the various reporting deadlines for the project as a whole. At one level of analysis (perhaps in terms of project management), this is an undesirable mode of operation. There is, however, a sense in which the process of collaboration was self-organizing in as much as the group was able to formulate its own agenda and work programme to suit a communal perception of progress.

As a closing comment with regard to the process of collaboration, there is a lesson to be taken from the observed relationship between disciplinary affinity and the structural level at which collaboration occurs. This point was well demonstrated by the divergent approaches to collaborative writing exhibited amongst the social science group (two anthropologists and a sociologist). When composing joint written reports, the two anthropologists were able to compose text almost on a sentence by sentence basis, integrating their data and observations at the level of the statement. In contrast, when the sociologist became involved, the focus shifted to the paragraph or section and integration occurred through thematic links. Although both sets of interactions were considered fruitful by all parties, it is interesting to note that even a modest disciplinary discontinuity can strongly influence the process of collaboration.

Collaboration Between the Disciplines as Understanding

When we understand, we take ownership of a piece of reality of which we had been unaware. Our own reality is thereby enriched and at the same time subtly changed. Collaboration as understanding is concerned with this phenomenon. By prompting researchers from different disciplines to work together towards some common aim, we are inviting them to enrich each other's reality. The hope (or design?) is that in combination they will be able to describe a more representative and thereby useful picture of

what we perceive to be a complex world. Collaboration without understanding is largely devoid of utility.

Although advice on how to understand and be understood effectively is widespread, much of it is superficial and oriented towards instructing and convincing rather than advancing comprehension. Within an intellectual framework this distinction is crucial. A deep and comprehensive form of understanding is required at the level of cross-disciplinary collaboration. Because each individual researcher is positioned within a web of interlocking knowledge and associated meanings, the transfer of understanding is best addressed at several levels. For example:

To understand the meaning of a sentence or whole discourse in an argumentative context, one should not examine merely the words within that discourse or the images in the speaker's mind at the moment of the utterance. One should also consider the positions which are being criticised, or against which a justification is being mounted. Without knowing these counter-positions, the argumentative meaning will be lost. (Billig, 1996: 91)

If understanding is to be a product of collaboration, it clearly has to be recognized as a complex construct.

It is beyond the remit of this text to delve any deeper into the nature of understanding between the disciplines. What we seek to suggest here is a structured framework for discussing the issues surrounding collaboration between the disciplines using evidence from a single project. However, we would draw on our experiences of the project to emphasize two areas where the relevant literature supports the available evidence. First, there is an inertia inherent in all our understandings which was effectively described by R.S. Wurman when he stated that: 'we tend to perceive the things that relate to our pre-existing interests and attitudes – either to support or refute them. People have a tendency to shun or refute information that contradicts these, whether consciously or not' (Wurman, 1990). Second, there are ways in which the effectiveness of collaboration as understanding can be improved. The conceptual framework suggested by Billig (1996) is again of interest here, as he suggests an analysis of what he terms '*witcraft*' or the skills of argumentation. For example: what is seen as a persuasively structured argument? What style of presentation is effective?²⁷ In the case study described earlier, it is debatable to what extent a common understanding of the function of the model was essential to successful implementation. Different disciplines will evaluate quality (of design and function) in different ways, influenced by the epistemological, ontological and teleological underpinnings of the fields of science to which they have been exposed. Whilst we have no evidence that variation in such 'epistemic lifestyles' (Shackley, 2000) inhibited communication and understanding, we would suggest that their negative influence may not be so significant in cases where there is no intra-disciplinary debate or where expertise and ignorance can be more clearly delineated.

Collaboration Between the Disciplines as Utility

Collaboration as utility relates to the explicit and implicit advantages that emerge from collaboration and can be interpreted as the benefits or fruits of the venture. These benefits may include other tasks such as understanding and negotiation, but they will also relate to the stated aims and goals of the project as a whole.

Again, judgment of relative success is made difficult by the relationships between this and the other benefits. Furthermore, utility accrues not only to the project as a whole but also to the participants (researchers) and others who have more indirect relationships with the study. However, although utility clearly extends to encompass emergent features of the work such as the experience of collaboration, there is a limit to how far any interpretation of possible sources of utility can be justified. Simply put, a comprehensive listing of sources of utility is problematic to identify, define and measure.

The significance of collaboration as utility has relevance to the project through the additional benefits gained over and above those that would have accrued if the disciplines had remained intellectually isolated. A subset of these benefits can be clearly identified:

- Emergence of a set of tools (including a common vocabulary and dominant metaphors) which will make further collaborative work more productive.
- A concern for some of the broader aspects of the problem set which, in turn, are also of interest at a policy formulation level.
- Utilizing informed criticisms from members of other disciplines to challenge accepted axioms and methodological issues.
- Development of a micro-simulation model which can be manipulated as easily by the social scientists as by the computer modellers.

This form of utility only became evident in the closing stages of the micro-simulation model development. By participating in the developmental phases of the model, the social scientists were able to react to the first demonstration simulations in a constructive way. Because they already had a 'feel' for the structures and processes being represented, they were able to contribute towards the refinement of the model's performance. Furthermore, the agenda for utilizing the model was unhindered by queries concerning its validity and capabilities, as these types of issues had previously been addressed to the satisfaction (negotiated consensus?) of all parties. A significant ramification of this observation is that the model was not, of itself, the final element in the modelling process. Data ownership was not observed to be a significant point of conflict, perhaps because each group was able to identify a stake in the model and its subsequent use. The social scientists were to be involved in the model verification process which entailed presenting the model's output to a group of farmers in the field. Dialogue between the disciplines (through query rather than negotiation)

was prolonged far beyond the point at which it would normally be observed.

Collaboration Between the Disciplines as Knowledge Integration

This final product of collaboration is in many ways a specific case of collaboration as utility. First, we would mention that from a methodological standpoint, the various levels at which integration can be achieved need to be distinguished. Three epistemological levels at which integration can occur are clearly identifiable. 'Data integration' concerns the use of combinations of raw facts and figures. 'Information integration' relates to quantitative and/or qualitative data that have been analysed for trends, or tested against hypotheses. Second, 'knowledge integration' occurs where a synthesis of contextually homogeneous and epistemologically rigorous information is achieved. This data-information-knowledge axis constitutes a core procedural element of the scientific method and is no less significant as a classification system for integrating the contributions of different disciplinary researches. A significant feature of this classification is the associated sets of activities that support the various levels of integration. The most important of these will involve scoping how, when and in what formats different types of data, information and knowledge will be generated through the collaboration. Failure to consider how different contributions are to be formally coupled or integrated can be seen as one of the causes behind criticisms of poor quality in cross-disciplinary endeavour. Maintaining the excellence and integrity of disciplinary contributions is a prerequisite for credible, robust interdisciplinary science. Much more work is needed to develop 'mapping functions' between qualitatively different knowledges if the benefits of integrative science are to be realized.

Although collaboration within the project took place at all three methodological levels described earlier and between a diverse range of cross-disciplinary groupings, there was little explicit debate concerning the appropriate degree of integration. Rather, a number of regular and insightful queries were voiced at various times during the project: should the various contributions be merely coupled as a sequence of individual studies that feed data and information onto the next activity, or coordinated as a fully integrated piece of work? Can areas of synergy be identified a priori? And how should the appropriate degree of integration be achieved: by the researchers themselves or by a third party? Doubtless these questions are best considered during the project design stages. However, they may not be at the forefront of the researchers' minds at this time due to the practicalities of project design and budget constraints (that is, resources are very often not available for a detailed examination of cross-disciplinary issues during project preparation). In thinking about potential opportunities for cross-disciplinary collaboration in terms of the queries posed earlier, the concept of 'seams of complementarity' was found useful. The use of the term 'seam' here is meant to convey the idea of commonality in two

dimensions, one of which cuts across the disciplines, the other crossing methodological levels (data, information, knowledge).

Seams of complementarity are areas of potential synergy between the various disciplinary activities within a project. The potential for exploiting these areas should be explored prior to embarking on the project's work plan. Whether the opportunity is concerned with data provision by a social scientist for a computer modeller, provision of a predictive model by a modeller for a social scientist or comparative surveys by different groups of researchers, the possibilities need to be explored and decisions made regarding the format and level of collaboration/integration required. Not all the opportunities for collaboration are evident prior to project commencement and occasions for collaboration emerge throughout the course of the research, although some of these may be deleterious to the project as a whole. Hence, collaboration between the disciplines is an evolving set of opportunities, which requires management and supervision if it is to be exploited for the overall benefit of the project.

Discussion and Conclusions

The evidence upon which conclusions concerning collaboration between the disciplines can be based comes from observations and impressions of the interactions between researchers involved in a specific project. Conclusions based on this information should therefore be treated with some discretion for three reasons. First, the study involved limited systematic data collection in an empirical sense. No hypotheses were tested and no theory examined. Second, and as noted in the introduction to this paper, there has been no formal attempt to investigate or analyse the psychological or sociological aspects of collaboration. A lack of comment regarding the significance of personality is perhaps this contribution's most serious deficiency, as the character and temperament of those individuals involved in the project had a clear influence on the dynamics of cross-disciplinary interaction (both in terms of the tools and the products of collaboration). Third, the specificity of the study plainly limits the extent to which we can draw generalizable inferences. The details of who was involved in the project (in disciplinary, cultural, linguistic and status terms), the objectives and the subject matter of the project, all serve to constrain the authority of this study's findings. Despite these caveats, there are several interesting threads of evidence that contribute towards the development of a richer picture of cross-disciplinary collaboration, and it would be remiss if we were not to draw attention to three key points which emerge from the study.

The first point we would make is that genuine collaboration between the disciplines has utility in its own right. The development of a common vocabulary and a style of dialogue (negotiation in this case), the recognition of significant elements of metaphor and the emergence of dominant metaphors, and the acceptance by the different disciplines of an intermediary, all require time and contact. Learning to manipulate the tools of

collaboration constitutes a learning curve which collaborating researchers explore together. However, both time and contact are valuable, and often limited, resources within the framework of an interdisciplinary research programme. Where such resources have been expended therefore, we would suggest that there is an argument to be made for retaining the value of the investment.

The experience of involvement in a genuinely cross-disciplinary discourse is clearly of benefit to the individual researcher in both educational and career terms. However, the utility of such collaboration to those bodies which commission research programmes has traditionally focused on the benefits to policy formulation. Significantly less attention has been paid to the experiential value which is contained within a cross-disciplinary research group and which is lost when the members go their separate ways. This should not be interpreted as an argument for retaining the same research group across several research programmes simply because they have worked together successfully in the past. Such an ill-advised strategy would likely result in intellectual stagnation and the emergence of a 'meta-discipline' formed from debased versions of the component disciplines. Consequential loss of the diversity of scholastic contribution, which is such a desirable feature of cross-disciplinary work, would clearly be counter-productive.

A more appropriate model would involve the maintenance of a core team, the precise make-up of which might reflect the central thematic components of the research programme and may include any intermediaries whose contributions have been found useful during past studies. The aim is not so much to *maintain* continuity of *knowledge* as to *retain* continuity of *experience*. For example, we noted earlier that the determinants of successful collaboration have as much to do with the personalities involved as they have with the mechanics of common vocabularies or the emergence of dominant metaphors. Hence, the latent potential for successful collaboration is possessed by individuals in a form that defies transfer. The particular characteristics of the tools of collaboration are specific to each case, because they are a partial function of personal interaction. Information relating to the use of tools in one case will not guarantee successful use in another.

The second concluding point concerns the planning and resourcing of cross-disciplinary activities. Previous experience with interdisciplinary work has emphasized the point that substantive and meaningful cross-disciplinary collaboration will not miraculously 'emerge' from either physical or intellectual proximity. The project described in this paper demonstrated that, by explicitly planning for and managing interdisciplinary interactions, a high degree of data, information and knowledge synthesis can be achieved. Several lessons are evident. For example, defining the products of collaboration in the project proposal and listing them in the work plan will prevent collaboration being an ad hoc component of the project, engaged in when time allows or inclination is aroused. Responsibility for the products of collaboration should be clearly assigned and a

specific budget allocated for achieving them. The nature and potential of the 'seams of complementarity' described earlier need to be identified at an early stage. Whilst it is beyond the scope of this text to hypothesize about effective or efficient methods for identifying and exploiting seams of complementarity, the direct evidence from the project suggests that early formalization of the nature, level and mechanisms of collaboration is beneficial.

Third, the observations made during this study have ramifications for the training of researchers. The skills and knowledge required to operate effectively not just within, but as a positive contributor to, a cross-disciplinary research team are dissimilar to those required to function effectively as a lone researcher or within a narrow disciplinary team. These skills will enable researchers to: (1) integrate perspectives that come from different paradigmatic, epistemological, and disciplinary traditions; (2) generate abstract representations of phenomenological structures and processes with which to explore problems; (3) communicate and interact effectively with co-researchers from other disciplines. We suggest that these skills would be promoted through competency in: (1) systems thinking; (2) modelling (both conceptual and formal/symbolic); (3) written, verbal, and visual communication.⁸ Whilst these competencies will be required by all researchers working in cross-disciplinary teams, we are also mindful of the significant role identified during the study for managerial and coordination functions. Cross-disciplinary team leaders will also therefore require an additional set of skills in structuring and managing the nature of interaction between team members and in managing data, information, or knowledge integration.

We note that if cross-disciplinary collaboration is a stated aim of a research programme or project then sufficient resources need to be provided to support it. Again, making the products of collaboration a specific element of the proposal and work plan will aid budget estimation and provide an audit trail for the interdisciplinary aspects of the research. Contrary to current funding trends, we would stress the benefits of a separate budget element to support cross-disciplinary collaboration. Expecting collaboration to be funded out of the various disciplinary groups' own budgets both undervalues (and in a way compromises) the utility of interdisciplinary activities, and serves to promote the ad hoc approach to collaboration criticized earlier.

Finally, we would emphasize the point that the unification of different intellectual and academic fields is not simply a pragmatic alliance that operates mechanically and predictably. On the contrary, the process of creating new understandings provides opportunities for engaging in meaningful debate about theory, methodology and technique, to the benefit of all those involved. This article tentatively identified some of the tools of collaboration that can be utilized to create new understandings. We have also mentioned four specific products of collaboration and discussed their meanings in terms of the project studies. As a parting observation, the following simple piece of advice is offered: 'As you learn about something

try to remember what it is like not to know. This will add immeasurably to your ability to explain things to other people' (Wurman, 1990: 130).

Notes

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1. Significant exceptions to this lack of innovation being the contributions of Judge (2002) on the use of metaphors as vehicles for transdisciplinary discourse and Romm (1998) on the reflexive nature of interdisciplinary practice.
2. We would guide the reader to the substantive work being carried out on Conceptual Integration (Turner & Fauconnier, 1995) and Cross-domain Meaning (Cummins, 1993) as examples of contemporary developments in this field.
3. We would note that one limitation of many practical instances of collaboration between the disciplines is that collaboration per se is seen as the goal without due attention being given to its various dimensions.
4. A somewhat crude but nonetheless genuine representation of the significance of this factor.
5. See for example the seminal collection of papers in Ortony (1993) or the work of Steiner (1975). Note that analogy has been considered as a special case of metaphor (for example, by Gentner & Jeziorski, 1993) and we will therefore use the latter term to include both phenomena.
6. By indirectly here we indicate that whilst 'complexity' and how to manage it was never an explicit issue, it was the underlying subject matter of other debates.
7. This framework can be seen to build on the distinctions made by Aristotle between Logos, Ethos and Pathos.
8. The written element of this skill set will include non-language representations such as diagrams and illustrations.

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