1. Introduction

Ideas of interdisciplinarity have often found practical expression in research at the interface of environmental science and policy. Indeed, 'joined-up' thinking is widely considered a precondition for developing holistic and integrated responses to problems of sustainability in society (Holdren, 2008); a process in which the natural and cultural dimensions of environmental issues can be marshalled around a common sense of intellectual purpose and endeavour. And yet, if it is one thing to assert the idea of interdisciplinary research as central to the ambitions of sustainability science, it is quite another to devise policy interventions that capture and reconcile often divergent understandings of a given problem. After all, a common aspect of interdisciplinarity is that it pulls together expertise in ways that make approaches to problem solving *not only* multidimensional in outlook, but coherent in their conception of the world. This is a daunting task not least because the issues upon which agendas for environmental science and policy seek to act are often emergent and novel in form. Interdisciplinary research means, in part, devising new theoretical constructs in which assessments of environmental problems can be made.

One of the contexts in which this problem is keenly felt, and which forms the focus of this paper, is in the development of holistic approaches to assess environmental risk. Developing these assessments is arguably key to the political and regulatory culture of contemporary environmental management, but as we shall see, the process of conceptualising and operationalising them in an interdisciplinary fashion is fraught with theoretical and methodological challenges. The purpose of this paper is to consider what some of those challenges are by drawing on a recent research project examining the issue of microbial pollution of surface waters.

In particular, the paper reflects critically upon efforts to develop an interdisciplinary assessment of the factors that may affect the transfer of potential pathogens from livestock farming systems to surface waters. This is a significant concern of the contemporary environmental protection agenda (Kay et al., 2007). Manures and excreta produced by grazing livestock are an important resource for farmers, but public exposure to the pathogenic microorganisms contained within these can lead to gastro-intestinal illness, for example infection caused by *E. coli* O157. Pathways to exposure may occur in a variety of ways, such as by ingesting contaminated waters through downstream recreational bathing (Graczyk et al., 2007) and through food consumption, for instance by eating contaminated shellfish (Schets et al., 2007). Alongside these consequences for human heath, microbial pollution carries with it an economic burden. In the UK it has been suggested that gastro-intestinal illness caused by *E. coli* O157 alone is estimated to cost over £1 billion per annum in lost productivity and around £30 million annually in healthcare (Jones, 1999). Moreover, the economic 'knock-on' effects of illness among human populations are potentially very significant for rural areas where agricultural, leisure and tourist economies are dependent on wider consumer confidence.

This papers explore the prospects for developing a holistic assessment of the factors that underlie and create these microbial risks[1] as the basis for targeted mitigation at the farm scale. It begins by introducing the wider policy and regulatory context in which a concern to manage microbial risks is now situated, and goes on to explain how an interdisciplinary approach might begin to capture the cultural[2] and natural processes that come to influence them. In particular, the paper describes a procedure in which a hypothetical construction of factors driving the transfer of microbial pollutants from land

[1] Microbial risk is understood in this paper as the product of likelihood of microbial contamination and magnitude of microbial impact on watercourses.
[2] In this paper we use the term 'cultural' as shorthand for the social and economic relations that define environmental risk, since in much environmental scholarship it is the term 'culture' that is dialectically related to the word 'nature', and with it, the concerns of natural science. See for example Whatmore (2002).

to surface waters was characterised and then subject to deeper rationalisation and refinement through the technique of expert elicitation. As a result the paper addresses some of the theoretical and methodological issues and conundrums that emerge from attempting to conceptualise an operational risk system by bringing quite different disciplinary positions to bear upon its construction, and with this, identifies some of the issues arising for environmental researchers when seeking to turn specialist assessments of risk into transdisciplinary - 'whole system' - knowledge. At the heart of the paper's argument is the need to come to terms with contrasting assessments of how theoretical representations of environmental risk work, and further, the need to address inherent differences in how cultural and natural processes can be accounted for. As a result of this analysis we move towards a conclusion that highlights the need for building critical 'unknowns' into assessments of 'known' risks. The paper suggests that sustainability science, such as work conducted on the issue of pathogen transfer from livestock farming practices, must recognise the partial nature of its assessments. How these uncertainties are conveyed in the uptake and application of risk assessment tools and models is, we suggest, just as important as seeking to render complex risks amenable to final prediction by way of empirical knowledge.

2. Research Context

The insights of this paper were developed under the auspices of a research project examining how farm management practices and circumstances can promote, limit and prevent the risk of microbial watercourse contamination [3]. The study employed a Faecal

[3] The research was funded under UK research councils 'Rural Economy and Land Use programme' (RELU), project code: RES-224-25-0086 (www.relu.ac.uk). Its focus was on the Taw Catchment in North Devon, UK, and has involved: an extensive survey of farmers across the Catchment eliciting attitudes and practices towards manure, land and livestock management; detailed microbial monitoring of water courses on ten of these farms, a review and mitigation methods; and a programme of public participation and

Indicator Organism (FIO) approach to researching and understanding pathogenic risks. Present within all human and livestock faeces, FIOs are bacteria indicative of faecal pollution and therefore potential pathogen presence. Central to the concerns of this paper, the project has also sought to develop a FIO risk assessment tool for farms, one designed to conceptualise the physical and cultural factors influencing the loss of faecal bacteria as the basis for targeted policy inventions.

The water policy context to these efforts has been described elsewhere (see Kay et al., 2008a). Designing risk assessment management plans are increasingly central to the regulatory environment within which farm practices now take place. In the UK for instance, state and quasi-state apparatus responsible for issues of environmental protection have introduced a range of mandatory measures and guidance for helping farmers to limit contamination of surface waters at the farm scale. These include the Department of Environment, Food and Rural Affairs soil and manure management plans (Defra, 2003; 2005a) and the Scottish Environmental Protection Agency's risk assessment for manures and slurries (SEPA, 2004). These frameworks are underpinned by more general responsibilities to 'codes of good agricultural and environmental condition' and are central to the conditions under which farmers can participate in new environmental stewardship programmes, such as Defra's Entry and Higher level stewardship schemes (Defra, 2005b). The wider agricultural policy context driving these developments in the UK and elsewhere has been well rehearsed (Wilson, 2007). European farmers have been placed increasingly at the centre of a 'public goods' model of the countryside where mandatory responsibilities for environmental protection at the farm and field level exist alongside an increasing 'marketisation' of environmentally friendly products (Buller and Morris, 2004).

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debate in which emerging scientific evidence was explored in relation to wider understandings and assessments of environmental risk.

Within this policy context there is a need to develop sustainable food systems that, by way of integrated approaches to land management, can effectively manage the wider, and often diffuse, impacts of agriculture on society and economy. Managing for the human health implications of ingesting pathogenic microorganisms either through recreational bathing or the consumption of food is an important driver for fostering assessment frameworks to assist both mandatory and voluntary action, not least given the exigencies of emerging legislative frameworks such as the EU Water Framework Directive (Kaika, 2003) and the EU Bathing Water Directive (Georgiou and Bateman, 2005). Thus, one of the purposes of our research has been to develop a conceptual framework within which potential pathogenic risks can begin to be assessed. What this amounts to, in effect, is an aspiration to construct a 'whole system' conception of microbial risk that can ultimately inform the development of a prototypical risk assessment tool for practical use by policy makers, environmental managers and farmers. A characterisation of this tool is reported on elsewhere (Oliver et al., 2009). The purpose of this inquiry is to examine the issues embedded in setting parameters around this tool's underlying conception of risk and then eliciting values for it.

3. Characterising an Interdisciplinary Risk System

As Chadwick *et al.* (2008) have argued specifically in the context of microbial watercourse pollution, understandings of environmental risk need to be grounded in a diversity of disciplinary perspectives. We are a research team comprising expertise in microbiology, hydrochemistry, soil hydrology, manure management, agricultural geography and rural sociology. We have worked on the basis that this expertise forms a reasonably diverse 'experience-base' to help identify what the cultural and natural parameters of a FIO risk system[4] may, in principle, be. We say 'experience base' rather than simply 'evidence base' because the process of identifying discrete factors or variables that may constitute a set of whole system parameters means combining both reliable knowledge into system variables (i.e. factors that we have confidence will have a bearing on FIOs as a result of empirical study) but also working assumptions or 'hunches', based on anecdotal evidence, about variables that may or may not have been studied in the context of pathogens (i.e. factors that seem to be relevant to FIO behaviour but of which we cannot be sure). In this we have found it useful to draw an analytical distinction between *direct* and *indirect* drivers of FIO risk in defining the characteristics of our risk system.

Direct drivers of risk concern variables in our hypothetical system that have an immediate and tangible control over the potential occurrence of FIO transfers from land to water. They are factors that operate at a practical and physical scale of expression, and imply causal connections that are, in principle, observable and definable within farm environments. Direct drivers presume, and to some extent may already encompass, an emerging evidence base in order to validate their place within a risk system. In general terms, the direct drivers we address in this study reflect the empirical work of natural science research, and in our system is reflected in a four-fold categorisation. In particular this categorisation draws inspiration from other environmental risk indexing work most notably the empirically informed 1990 phosphorus index (see Lemunyon and Gilbert 1993). It encompasses issues of:

- *Source* **-** incorporating those factors that determine the fundamental presence and origin of FIOs within farm environments. These can include: livestock grazing density (Aitken, 2003); faecal inputs and their associated FIO die-off

[4] By 'risk system' we mean a definable and hypothetically bounded set of variables that characterise the drivers of an environmental risk, in this case, the transfer of FIOs from agricultural land to surface waters.

rates (Oliver et al., 2006); manure application methods (Hutchison et al., 2004); and grazing duration (White et al., 2001).

- *Transfer* **-** encompassing those factors encouraging FIOs to start their journey to a watercourse including, for example: field slopes and shapes (Abu-Ashour and Lee, 2000; Crowther et al., 2003), soil hydrological properties (Artz et al., 2005) and cell interactions with soil particles (Muirhead et al., 2006).
- *Connectivity* **-** encapsulating those variables that link source and transfer mechanisms to a receiving water such as artificial field drainage (Oliver et al., 2005), overland flow distance (Collins et al., 2005) and direct defecation of excreta into streams (Davies-Colley et al., 2004).
- *Infrastructure* **-** embodying human material interventions and constructions in the landscape that underpin the presence and movement of FIOs in a given farm environment (e.g. Edwards et al., 2008). These can include: manure storage capacity and associated conditions (Smith et al., 2001) but also point source inputs of FIOs associated with the hard standings and buildings used by livestock (Kay et al., 2008b).

In contrast, indirect drivers of risk have a more tacit influence on FIO risks. They encompass those factors that condition FIO risk more widely. For instance, while it may be possible to infer that the source risk of 'grazing density' tangibly influences the magnitude of FIO risks in a given farm landscape since variations here will govern the number and rate of organisms excreted onto pasture, the issue of grazing density is, of course, a land management choice shaped by a wider set of political, economic and attitudinal influences. Indirect drivers are therefore designed to enhance the explanatory potential of a risk system by acknowledging issues of both 'structure' (for instance, the influence of policy measures and market incentives) and 'agency' (for example, the effect of values) in processes of farmer decision making. This is a key, and longstanding, analytical distinction within the study of social relations (Giddens, 1984) and central to many theorisations of agricultural change (Wilson, 2007). Indeed, it is in the interplay of these factors that rural studies have sought to make sense of where key determinants of farmer action lie (see for instance, Wilson and Hart, 2000; Burton and Wilson, 2006). Yet unlike issues of 'source', 'transfer', 'connectivity' and 'infrastructure', here it is more awkward to identify a set of variables that can be packaged into a logical and discrete sequence of influences on microbial watercourse pollution, or a set factors that can be systematically linked to material processes at the farm level. Economic and political drivers of FIO risk, for instance, originate in contexts far exceeding the farm gate, such as political arenas that shape prevailing market and regulatory conditions, while farmer attitudes and values are not only difficult to uncover, but tend to be multifaceted and unstable (Burton and Wilson, 2006), and therefore defy neat typological prescription (Fish et al., 2003). One of the vexed tasks facing the development of an interdisciplinary risk system is therefore to translate a diffuse and nebulous set of issues into a functional set of factors; ones amenable to the pragmatic demands of risk assessment. Accepting that these structural and attitudinal influences are part of a spectrum of overlapping influences, and that, unlike direct drivers, no evidence base exists for understanding determinants of risk in a specifically FIO context, our research suggests that indirect drivers of risk can be categorised in four key ways:

- *Income and resources* - addressing the material and financial resources that influence the uptake of measures to limit and prevent FIO risks occurring. Resource constraints (such as access to labour) have been widely recognised to influence farmer/enterprise decision making (e.g. Lobley and Potter 2004).

- *Knowledges and affiliations* - encompassing the conditions under which the intellectual capital to manage for FIO risks may be communicated, learnt and ultimately deployed. This element attends to the wider social production and exchange of information and knowledge amongst communities of farmers (such as training and accreditation), a key determinant of enterprise behaviour (Tsouvalis et al., 2000)
- *Non-agricultural activities* **-** reflecting the influence of wider recreational associations with landscape on management attitudes to water quality risks. This component situates farm behaviour in the context of multifunctional land use (such as recreational pursuits taking place on land); and therefore indexes a key explanatory framework behind motivations to act in contemporary agricultural systems (Wilson, 2007)
- *Farm structure and trajectory* - incorporating variables that link capacities and inclinations to manage for risk with prevailing household and enterprise circumstances, (such as type of ownership and stage in lifecycle). This element interprets decision making as a function of more tacit 'path-dependencies' (Wilson 2008), both economic and cultural in kind. Explicit recognition to the influence of biography and economic transition is given credence in these aspects of the characterisation.

A detailed overview of the variables that comprise these direct and indirect categorisations is provided in Tables 1 and 2 respectively, and is accompanied by a general rationale for their inclusion in our system.

4. Creating an operational system through expert elicitation

Designing a hypothetical risk system that draws on the distinction between direct and indirect drivers is useful for it allows us to begin thinking systematically about what types of evidence would be needed to operationalise the system in practice, and how disciplinary responsibilities might begin to be assigned in such an undertaking. Perhaps most significantly it provides a framework in which the explanatory potential of social and natural sciences are understood to be co-dependent. By definition, the variables which comprise any given system are open to critical scrutiny, but we suggest that, by adopting a multidimensional, experience-based, approach to the task of system building, a rich and plausible picture of factors driving FIO risk begins to emerge.

However, the process of constructing system parameters is not an end in itself, for it tells us nothing about level of significance we might wish to attach to one particular variable over another within the system. As such, if the first task for developing a FIO risk tool is to establish a set of parameters within which microbial risks can be situated, the second is to establish which elements are 'more or less' important to the system. To do this we have followed a body of experimental methodological work that has sought to develop heuristic assessments of problems through the use of expert elicitation techniques, not least in the context of environmental science (e.g. Geneletti, 2005; Nguyen and de Kok, 2007; Ye et al,. 2008).

Expert elicitation is a means by which we can refine understandings of research problems by exposing them to wider critical scrutiny. Like the issue under consideration here, they are typically deployed in problem contexts where theoretical frameworks are novel and empirical understanding is incomplete. Some applications of the technique, such as through the use of the Delphi method or one of its many variants, are characterised by a desire to reach consensus, building iteration, interaction and feedback into its approach (Murry & Hammons, 1995; Chu and Hwang, 2008). Consequently, they are designed to enable expert judgments to forecast and establish priorities in arenas of science policy that would otherwise remain intractable. That is to say, they allow policy programmes to be devised on a scientific basis in the absence of conventional forms of scientific evidence. The argument here is that elicitation techniques allow policy makers to craft judicious responses to emerging problems, not only because the process may reveal strong areas of (otherwise unrecognised) agreement but also because they help characterize and clarify regions of uncertainty (Rizak and Hrudey, 2005). Yet, as von Kraus et al. (2004 p.1515) note, "in situations where uncertainty is high, different experts may have different interpretations of the data available, and the diversity of opinions may be far larger than that which is suggested by consensus documents, such as risk assessment reports". Not surprisingly one of the issues facing those who use these techniques is how to inform reasoned responses to policy problems without also propagating the idea that scientific debates are somehow settled and resolved. As Hoffman et al. (2008, p.697) have put it in the context of pathogenic risks: "Expert elicitation ultimately is a complement, not a substitute, for primary research…[ ]… But it can provide a practical aid to the better management of safety in complex systems where perfect information is rarely available but better information might be".

4.1 Approach to elicitation

In practical terms we initiated a process of expert consultation in which individuals with different disciplinary expertise were asked to pass judgment on the relative importance of possible controls on FIOs. The elicitation process followed Booker and McNamara (2004, p.221) in understanding expert knowledge as that encompassing "what qualified individuals know with respect to their technical practices, training and experience" and made a distinction between those working in a natural science setting as having the expert knowledge to gauge the relative importance of the direct bio-physical and management variables, and those working in the context of social-science as able to pass judgment on indirect cultural processes and structures.

Like the distinction between direct and indirect drivers made above, the purpose of disentangling the consultation process into perspectives from the social and natural sciences is designed to make an analytical and practical, rather than empirical and substantive, distinction in how we can conceptualise and understand FIO risk. The process of selecting participants in the elicitation process was designed to ensure that a range of cognate science and social science areas of research would be represented. For those working in a natural science context we solicited the views of those with expertise and standing in academic microbiology, soil and environmental science, as well as members of the policy community with professional investments and backgrounds in microbial/waste management processes. For those working in a social science context we solicited the views of those working in rural geography, agricultural studies, agricultural economics, rural sociology and political science. Whilst those with natural science expertise were required to have experience within the sphere of FIO research in order to qualify for inclusion within the consortium (c.f. Cornelissen et al., 2003), this was not the case in the social-science consultation, since as we have made clear above, no substantive research areas exist to define an expert group in this way. Even so, all of the social scientists included in the process were identified on the basis that their background intersected with interests in rural environmental change, of which watercourse pollution was a substantive, or at least, related concern.

At least one of the implications of this process is that different explanatory logics and types of analytical and definitional precision have to be created for members of expert consortiums. In the natural science consultation it was recognised, for instance, that expert responses could be potentially variable depending on whether views were elicited for *pathogenic* or *FIO* risks. In a technical sense, FIOs are one strand of a larger pathogenic issue, a crucial difference to a respondent with precise expertise in this research area (such as microbiology)[5]. In the social science context, this definitional problem is inverted. We reasoned that FIOs would mean very little to those with training in social science and care was taken to explain 'FIOs' as a framework for examining potential *pathogenic* risks to watercourses.

The process was conducted through a standardised electronic scoring schedule, in which experts were instructed to weight the relative influence of a given risk factor on a continuous scale ranging from 0 (of no importance) through to 1 (of absolute importance). If respondents felt unable to weight factors with confidence they were instructed to leave potential entries blank. A qualitative dimension was also included in that respondents were allowed to comment and elaborate on their choices should they wish to do so. In total 28 experts participated in the elicitation process, representing a response rate of approximately 80%.

It is of note at this juncture to recognise that this methodology is by no means the only way in which the task of eliciting judgment can be approached, and a case has been made for developing more interpretative and discursive approaches to risk and uncertainty characterisation (EA, 2008). The approach we adopted in this study was designed as a first approximation of expert knowledge, and was geared explicitly to the producing responses that could be operationalised easily within a prototypical risk assessment tool (Oliver et al., 2009). A deeper contextualisation of expert assessments of

[5] One way of illustrating this point is with regard to our risk factor 'animal type'. In an 'FIO' consultation, animal type might not be considered by experts a strong driver of risk, relative to other factors, because all livestock faeces contain considerable FIO content. But this is not necessarily the case should we have devised the consultation around 'pathogens' *per se*. Here animal type may be considered more important (for instance lambs are also large cryptosporidium reservoirs). The definitional formula is not merely a technicality: it could significantly influence measures arising from risk assessment.

risk through, for instance, depth and interviews would be a logical development on the insight developments here (see for instance, Philips, 1999)

4.2 Gauging the relative importance of system variables

A general summary of statistics associated with the expert weighting exercise is shown in Tables 3 and 4. As an initial layer of analysis, the project team calculated the arithmetic mean of expert weightings for each variable as a way of assessing their relative importance to the system as a whole. Assessing relative significance in this rudimentary way begins the process of understanding where priorities for FIO risk assessment might lie. Thus, following this approach the expert elicitation process suggests that 'livestock access to streams' would be considered a key driver of risk on the basis of the natural science consultation, for it achieved a mean expert weighting of 0.82 among experts, the highest across all risk categories, and accommodates a strong negative skew in the distribution of weightings received. Other salient factors included the transfer risk of 'runoff potential' (0.73), the infrastructural risk of 'drainage' (0.72), and the source risks of 'stocking density' and (0.72) 'manure type' (0.66). In the social science consultation, key determinants of risk included whether a farmer had access to 'technical grants for waste management' (0.83), the extent to which farming activities were currently structured through 'participation in agri-environmental schemes' (0.69), and whether practices were embedded in 'organic farming' regimes (0.68). With a mean weighting of 0.58 the 'size of the holding' also constituted a higher ranking determinant of risk in the social science assessment.

By implication the consultation process also pointed to areas of our risk system where the impact of variables was considered relatively weak. So, for instance, while the results of the natural science consultation suggest that importance should be attached to 'livestock access to streams', another source risk 'livestock type' achieved a mean weighting of only 0.35, the lowest across *all* natural science risk categories. Likewise, the importance experts attached to the transfer risk of 'run-off potential' can be contrasted with issues of 'erosion' and 'preferential flow' potential, which returned mean weightings of 0.38 and 0.56, respectively. In the social science consultation, the significance experts assigned to 'size of holding' can be neatly contrasted with 'tenure of holdings', which returned a mean expert weighting of only 0.30. Moreover, the social science consultation placed little importance on lifecycle issues such as 'succession' and recreational factors such as the 'presence of public rights of ways on or bordering land'. Both these factors achieved mean weightings of only 0.26. Of course, the range of expert weightings received for each risk factor may be used in the future for uncertainty assessment (Refsgaard et al., 2007) and fuzzy modelling approaches but that is beyond the scope of this present paper.

4.3 Areas of expert consensus and disagreement

On the basis of this analysis our system begins to take shape as a framework in which distinctions about FIO risk can begin to be drawn. However, making judgments in this way tells us nothing about the extent to which experts agreed or disagreed about the relative importance of risk factors. Risk factors may be ranked high or low, but variables can have differing levels of consensus attached to them. This is an important underlying issue, for as we have shown, in discriminating between the relative influence of given factors, a risk assessment framework would also ideally aspire to focus on system variables that have a high degree of consensus attached to them across disciplinary boundaries.

The dimensions of this latter issue are expressed as box and whisker plots in Figures 1 and 2. For the natural science consultation there were a number of high and low ranking variables where experts displayed a high degree of consensus (i.e. a narrow interquartile range). So, for instance, the highly ranking source factor of ‘stocking density’ was accompanied by the lowest interquartile range and standard deviation (σ) among experts (see Table 3), suggesting that collective confidence in the influence of this variable was strong. Equally, there was close agreement among experts regarding some factors which were otherwise considered to be weak in their influence. The connectivity risk factor of ‘gateway location’, which returned a mean expert weighting of 0.39, would be a case in point here (σ =0.21). In the social science consultation there were also generally strong levels of agreement surrounding high ranking factors such as ‘technical grants’ (σ =0.19), but perhaps most notably, surrounding the influence of responsibilities under ‘cross-compliance’[6] (σ =0.17), a factor attaining a moderate expert mean weighting of 0.49.

Yet these findings have to be squared with variables where expert opinion was largely divided. In the natural science consultation there was considerable variability over the importance we should assign to infrastructural factors. For example, while the mean weighting for ‘farm tracks’ was ranked moderately at 0.40, some experts suggested its weighting should be as high as 0.80, while others considered it of no importance at all in driving risk, resulting in a standard deviation of 0.25 for this risk factor. How do we explain such discrepancies? At one level it may be argued that contrasting visions reflect an uncertain evidence base. For example, Edwards et al. (2008) note that a general awareness exist regarding farmyards as sources and contributors of pollutants to receiving waters but stress that few measurements have actually been made to quantify contaminant flux from these areas. However, even where empirical research exists, wide interquartile ranges can be returned. An interesting example of this was with regard to the

[6] In the UK cross-compliance embodies a set of mandatory conditions regarding good agricultural conduct and underpins state support for agriculture in the form of a ‘single farm payment’.

source risk factor of ‘aged faecal material’. Consensus here was weak (σ =0.28) despite empirical research from the 1980s reporting on patterns of release of FIOs from ageing faeces (Thelin and Gifford, 1983; Kress and Gifford, 1984).

Such discrepancies may well demonstrate the need to further consolidate understanding of some drivers of microbial watercourse contamination not only through future research agendas (Kay et al., 2007; Kay et al., 2008a) but in their effective dissemination across different knowledge domains, but we suggest there may be a deeper problematic at stake. At a more theoretical level this divergence may reflect tensions that inherently exist between making ‘whole system’ assessments of risk and the disciplinary nature of expertise partly informing the principle of expert judgements. In our risk assessment, respondents were asked to comment on the *relative* importance of controls across the risk system, but the basis of participation in the exercise was dictated, in part, by their status as authority figures with ‘specialist’ types of expertise: that is, by their knowledge of *particular* components of the risk system. And as the literature on expert elicitation argues in this vein, when individuals respond as experts in this way they tend to be overconfident in recognizing the influence of those factors that reflect their professional remits and worldviews. Or as Granger Morgan et al. (2001, p.282) put it “given their knowledge, …[the]… subjective probability distributions …[of experts] … tend to be too narrow”. In other words, precise notions of expertise tend to shape the emphasis placed on particular aspects of risk assessment, leading to divergent accounts of how a system works.

A telling example of this is in relation to two elements of the natural science assessment: ‘preferential flow potential’ and ‘animal type’. Whereas respondents with a background in microbiology weighted the former issue of lowest importance in the risk system, those with soil science interest ranked this highest. Conversely, whereas a number of microbiologists ranked ‘animal type’ as an issue of key importance, many experts in soil science assigned it low significance. How far should we be surprised by these divergent opinions? After all, preferential flow potential is a core concept of soil science and will therefore be central to the professional remit those working in this area of specialism. But this concern is outside of the formal scope of microbiology, where animal-led explanations of risk are likely to prevail. The data provide further examples of this issue. Responses to the risk assessment reveal that those natural science respondents working directly in the arena of FIO policy intervention and development consistently provide higher risk ratings to the importance of individual elements in the risk system than academic scientists, perhaps reflecting how professional investments and awareness in the given risk issue can tend to magnify *overall* understandings of risk. For example, grouping the natural science expert panel into non-academic policy experts, microbiologists, soil scientists and environmental scientists revealed that the policy-based experts ranked 17 of the 22 risk factors with higher mean weightings, and on one of these occasions (for the risk factor ‘farmyard drainage to watercourse’) the difference between expert groups, derived using an analysis of variance test, was significant ($P<0.05$). The policy expert group weighted this risk factor as 0.98 (clearly illustrating near universal agreement of the absolute importance of this risk factor), whereas the microbiologists, soil scientists and environmental scientists groupings returned average weightings of 0.64, 0.60 and 0.65, respectively.

In other words this initial analysis of results suggests that disciplinary and professional investments produce interesting distinctions in how FIO risks come to be conceptualised, though in making this claim we feel it necessary to exercise some caution here. Drawing conclusions in this way presumes that affiliations and expertise exist as a series of tightly bounded, and mutually-exclusive, entities, when in practice, this may not be the case. Disciplinary boundaries and identities are often quite fuzzy both in terms of professional practices and research preoccupations; while the world of academic research and policy driven science are often fundamentally entwined in terms of career pathways and research priorities. Nonetheless, we suggest that these findings point to one way in which divergent assessments of FIO risk might begin to be interpreted from an interdisciplinary perspective.

Notwithstanding the need to understand why these divergent responses arise, one of the key issues that such heterogeneity poses is how to arrive at overall assessments of risk that would allow a future risk tool to be operationalised in practice. The use of mean expert responses was our response to this approach, though it does not resolve the underlying ontological problem here: how to create a common, as in collectively agreed upon, vision of the risk system?

4.4 The indeterminacy of risk

To the theoretical conundrum of establishing a common vision we wish to add a further and final dimension. This concerns the issue of indeterminacy. One of the tacit assumptions underlying our analysis is that a given control on FIO risk has a consistent relationship with how a risk is influenced. That is to say, experts may or may not agree that one variable is more important than another in the system, but the assumption is that the *direction* of risk is clear. In many cases this assumption is fair. Certainly it is true of our direct risk factors. So for example it is clearly logical to suggest that the steeper a hill slope the greater the potential for run-off, and therefore risk of FIO loss from land, just as we can claim, with confidence, that the export of FIOs from land to water would be less likely under extensive grazing regimes. However, in the case of our indirect drivers, this principle does not necessarily follow. While it may be reasonable to infer that 'participation in an agri-environmental scheme' or 'receipt of technical grants' would be linked with a potential reduction in FIO risk, it seems much more problematic to make such connections with a number of other indirect variables. So, for example, the variable ‘length of time in farming’ is interesting in a social science context for it implies capacities and inclinations that may influence risk in a variety of ways. Recent entrants to farming may bring with them new models of working that are conducive to working within the mandates of modern environmental protection, but so too may they lack the very skill-sets that would come from longstanding involvement in a particular system of livestock farming. In other words, the system variable ‘length of time in farming’ embodies in it a range of influences conducive to different types of outcome. This indeterminacy seems to be true of ‘farm succession’, ‘size’ and ‘tenure’ of land farmed and influence of ‘debt’. Contrasting narratives of FIO risk could be assigned to these endemic characteristics and circumstance of a farm system.

Anticipating this response in the expert consultation, we examined this issue directly with social scientists. Alongside the process of assigning *importance* to system elements, we asked these experts to make judgments about how the *direction* of risk might unfold. To do this, experts were presented with a series of propositions about the potential influence of all indirect variables on FIO risk. Thus in the case of farm size, experts were asked to consider the proposition *‘The transfer of FIOs to water courses is less likely the smaller the area farmed’*. Experts could then offer different responses to these propositions to indicate the extent to which they agreed with the proposition or could offer a meaningful response to it. A summary of these propositions and the framework for expert responses is depicted in Table 5. The box and whisker plots, revealing extents of agreement between respondents to this aspect of the consultation, are displayed in Figure 4.

Not surprisingly the consultation identified some areas of social science agreement where the directional influence of variables is clear. Collectively, the response of the consultation suggests that ‘receipt of technical grants’ would be likely to lower FIO risks, as would ‘responsibilities under cross compliance’, ‘participation in agri-environmental schemes’ and ‘organic farming’, as well as ‘formal accreditation in land and livestock management’. Yet as anticipated, in other instances, the consultation raised profound disagreements over the directional influence of variables. Issues of ‘tenure’, ‘succession’ and most notably ‘farm size’ stand out here. While size of holding is a relatively high ranking factor, there was little agreement about the direction of risk we might attach to a particular operational farm scale. Many refused to draw neat conclusions. One suggested that “those with a limited area may have more of a waste disposal problem”, but pointed to alternative circumstances where size might imply farmers were “less intensive smallholders” with lower risks.

The consultation suggests therefore, that there is no consistent way of assigning risks to particular variants of some risk conditioning issues. We suggested in the section above that a fundamental problem for those wishing to create holistic conceptions of risk is how to ‘overcome’ differences in expert knowledge regarding how the system ‘works’. Here the issue seems to be rather different. Such indeterminacies are problems produced by the generic needs of risk assessment, not differences in expert opinion *per se*. It is tempting, for instance, to ignore issues such as ‘size’, ‘tenure’ and ‘succession’ because they cannot be standardized across a range of circumstances. But the message of this aspect of our consultation is that risk assessment frameworks should not only be generic in design but sensitive to context. In other words, size may well be an important generic variable, but we can only draw conclusions about its *determinate* influence when studying precise sets of circumstances.

4.5 Quantifying potential errors associated with expert weightings

The expert consultation exercise outlined in this study was designed to elicit indicative responses from experts in relevant disciplines that could help make an on-farm risk tool operational. Associated weightings derived through this process were eventually embedded into a cross-disciplinary toolkit to assess the risk of faecal indicator loss from grassland farm systems to surface waters (Oliver et al., 2009). While the statistical analysis of the data presented in this study centres on traditional differences in distributions of expert weightings for given risk factors there is a realisation that there is likely to be a degree of interdependency between weighted risk factors when incorporated into integrated risk management tools. It is when expert derived data is incorporated into decision support tools (DST) that we can begin to undertake a more in-depth analysis of variations in expert judgement. Whilst beyond the remit of this current study, it would be wise to undertake a full sensitivity analysis of any DST that accommodates expert judgement to determine the responsiveness of DST output to changes in individual risk factor weightings. For example, if DSTs inform end-users of an index of relative risk of a parcel of land contributing a pollutant to a watercourse then what would be the effect on the final risk index of a change in any single risk factor weighting of, for example, 0.01 or 0.1? Furthermore, which risk factors are most sensitive to these changes?

Reporting on the range of original expert weightings embedded within management tools enables researchers to assess the error placed on calculated risk indices when the standard deviations (or confidence intervals) of the mean for each risk factor weighting are taken into account. Given that different expert weightings (such as those derived in this study) carry different ranges of opinion we can begin to assess which risk factors contribute most to the errors intrinsic to expert weighted risk indexing approaches, thus allowing a decision to be made as to whether a risk factor might be justifiably omitted.

Perhaps more importantly, the ranges of difference in expert weightings can highlight risk factors to target for fundamental research to better align expert opinion.

5. Concluding remarks

In a paper speculating on future developments in the field of microbiology Curtis (2007) argued recently for the creation of numerically reliable, and widely applicable, explanatory frameworks for microbiological research; ones linked expressly to the needs of wider political and social agendas and involving the development of a "consilient and calibrated set of rules to describe and predict the behaviour of the microbial world as a system" (*Ibid* p.1). In this paper we have sought to examine some of the complexities that arise from seeking to foster such systemic and applied understandings of the microbial world. If we were to appropriate Curtis' vision for our particular purposes and take it to its logical conclusion, then this would be a process in which researchers would be able to calibrate real world livestock systems according to the intrinsic orderliness of potential pathogen transfer within agricultural environments. In so doing, it may be possible to start to make highly reliable judgments about the conditions under which microbial risks are present and thereby controlled.

The paper has described an experimental process in which such a system might begin to be imagined. Like many arenas of environmental sustainability there are few empirical reference points in which to begin navigating a stable pathway through the essentially complex and unbounded system of FIO risk. In this our research suggests that an interdisciplinary approach can greatly enhance the plausibility of a hypothetical system and can underpin the development of a new generation of study areas that are linking ostensibly disparate research areas together. The idea of 'diffusion pollution studies' (Lane et al. 2006), of which an account of FIO risk would ultimately be a part, is a case in point. Yet, so too has our research served to underline the substantive difficulties, both theoretical and methodological, in arriving at a shared picture of the world. The idea of building rule-governed, 'whole system', conceptions of environmental processes is itself a distinct, and by no means unproblematic, theoretical aspiration. Assuming that we can foster interdisciplinary teams to collaborate in this endeavour, the means by which we then arrive at internally stable conceptions of risk is by no means accepted or understood.

As we have shown, one of the paradoxes of building interdisciplinary pictures is that they necessarily emerge out of precise areas of scholarship, and this will mean that conceptual and analytical differences over how a system works will tend to be magnified as much as they will be diminished. One of the challenges facing those creating holistic approaches to environmental risk assessment is therefore how to develop methodologies by which such discrepancies can be overcome. In other senses, taking a whole system approach begins to reveal complexities that question the way we structure our representations of problems, and with this, the nature of our interventions. It may well be that some drivers of risk are indeterminate, which fundamentally alters the needs of risk assessment.

With these problems and challenges, we suggest, comes responsibility to design procedures that can acknowledge, rather than bury, endemic system uncertainties. This seems axiomatic given that theoretical representations of environmental problems reside as much in a world of policy 'readiness' as they do in the long term agendas of scientific research. Faced with the need to construct reasoned responses to emerging policy questions, such as the management and mitigation of FIOs, we need to be circumspect when translating highly tentative and contested constructions of environmental problems into expert systems with 'ready-made' answers.

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