The ecological research needs of business

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Summary

1. Businesses have an unrivalled ability to mobilize human, physical and financial capital, often manage large land holdings, and draw on resources and supply products that impact a wide array of ecosystems. Businesses therefore have the potential to make a substantial contribution to arresting declines in biodiversity and ecosystem services. To realize this potential, businesses require support from researchers in applied ecology to inform how they measure and manage their impacts on, and opportunities presented to them by, biodiversity and ecosystem services.

2. We reviewed papers in leading applied ecology journals to assess the research contribution from existing collaborations involving businesses. We reviewed applications to, and grants funded by, the UK's Natural Environment Research Council for evidence of public investment in such collaborations. To scope opportunities for expanding collaborations with businesses, we conducted workshops with three sectors (mining and quarrying, insurance and manufacturing) in which participants identified exemplar ecological research questions of interest to their sector.

3. Ten to fifteen per cent of primary research papers in *Journal of Applied Ecology* and *Ecological Applications* evidenced business involvement, mostly focusing on traditional rural industries (farming, fisheries and forestry). The review of UK research council funding found that 35% of applications mentioned business engagement, while only 1% of awarded grants met stricter criteria of direct business involvement.

4. Some questions identified in the workshops aim to reduce costs from businesses' impacts on the environment and others to allow businesses to exploit new opportunities. Some questions are designed to inform long-term planning undertaken by businesses, but others would have more immediate commercial applications. Finally, some research questions are designed to streamline and make more effective those environmental policies that affect businesses.

5. Business participants were forward-looking regarding ecological questions and research. For example, representatives from mining and quarrying companies emphasized the need to move beyond biodiversity to consider how ecosystems function, while those from the insurance sector stressed the importance of ecology researchers entering into new types of interdisciplinary collaboration.

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6. *Synthesis and applications.* Businesses from a variety of sectors demonstrated a clear interest in managing their impacts on, and exploiting opportunities created by, ecosystem services and biodiversity. To achieve this, businesses are asking diverse ecological research questions, but publications in leading applied ecology journals and research council funding reveal limited evidence of direct engagement with businesses. This represents a missed opportunity for ecological research findings to see more widespread application.

Key-words applied ecology, biodiversity, business, corporate social responsibility, ecosystem function, ecosystem services, insurance, knowledge exchange, manufacturing, mining

Introduction

The potential contribution of businesses to slowing or reversing losses of biodiversity and ecosystem services is enormous (Rubino 2000; Daily & Ellison 2002; Millennium Ecosystem Assessment, Business and Industry Synthesis Panel [MEA] 2005). Businesses have an unparalleled ability to move human, physical and financial capital around the globe; own and manage extensive land and resource holdings in some of the most biodiversity rich regions; manage supply chains that draw on and impact a wide array of ecosystems; and take strategic decisions that can influence consumer preferences and shape regional development patterns. Exhortations for businesses to incorporate better stewardship of biodiversity and ecosystem services into their corporate social responsibility (CSR) planning and reporting are commonplace (e.g. Lovins, Lovins & Hawken 1999; Jeurissen & Keijzers 2004). However, the measurement of biodiversity and ecosystem services that this will demand remains a significant scientific challenge. For businesses to devise strategies to protect, restore and enhance ecosystems is a greater challenge still.

We examine how research in applied ecology is helping to meet these scientific challenges and we scope opportunities for growing its contribution. We focus on scientific research activity as opposed to case specific applications of existing ecological knowledge. The distinction is important for understanding our design. Research in applied ecology aims to discover knowledge about ecological patterns and processes that will support new fields of application and new techniques that make such applications possible. As such, the role of the researcher in applied ecology is distinct from that of the environmental consultant, whose remit is to apply existing ecological knowledge to a specific situation. That being said, individuals may sometimes take on either role; individuals primarily employed as environmental consultants make contributions to research and researchers often undertake consultancies.

An extensive literature examines connections between scientific research and businesses and the influence that governments exert on these relationships (e.g. Dasgupta & David 1994; Nowotny, Scott & Gibbons 2003; Inzelt 2004; Etzkowitz 2008; Kruss 2008). The extent and nature of science to business connections varies across disciplines, but past studies do not provide insights specific to applied ecology. For example, Bel-khodja & Landry (2007) in Canada and Martinelli, Meyer & von Tunzelmann (2008) in England report on activities in the Life Sciences in general but do not resolve their data further.

We examine peer reviewed publications in leading journals to assess the productivity of existing collaborations between researchers in applied ecology and businesses. We examine applications for research council grants to determine the role of this type of public funding in supporting collaborations. Clearly, peer reviewed journal articles and research council grants provide only two measures of research activity and in the Discussion we consider the limitations of these measures and the suitability of alternative indicators. In the Discussion, we also review the economic theory that justifies public investment in collaborations between businesses and applied ecology researchers.

Next, we explore with businesses from three different sectors the types of research questions in applied ecology that they would find particularly useful. This exercise is designed to identify opportunities for expanding collaborations between businesses and applied ecology researchers, to ground discussions of what new types of collaboration might look like and to provide exemplars of forming questions in a common language for emerging issues. To do this, we draw on the model of recent question design activities conducted with public agencies and NGOs (Sutherland *et al.* 2006, 2008, 2009; Morton *et al.* 2009). However, these previous studies failed to engage end-users of ecological research drawn from the business community. Indeed, a key motivation for representatives from businesses to participate in the current question design exercise was because they perceived a need or felt a frustration that they could not access the relevant academic resource and that their priorities for applied ecology research were not being well understood or valued.

Materials and methods

PUBLICATION AND FUNDING OF RESEARCH ENGAGING WITH BUSINESS

To assess the contribution of existing collaborations between researchers in applied ecology and businesses to new knowledge production, we reviewed all primary research papers published in the two leading, international applied ecology journals in 2008 (200 papers from the *Journal of Applied Ecology* published by the British Ecological Society and 185 papers from *Ecological Applications* published by

the Ecological Society of America). Papers were scored for evidence of private sector involvement in undertaking the research as revealed in the authorship list, methods or acknowledgements. Where there was evidence of business involvement, we classified the type of business and the nature of their involvement by combining the original text with web-based searches for company details. We do not include universities or other private and charitable research institutions in our definition of businesses.

To assess the extent to which government research council grants support collaborations between ecological researchers and businesses, we examined research grants funded by and applications submitted to the Natural Environment Research Council (NERC), the UK government's primary funding agency for ecological research. We focused on the full range of NERC grants, including those intended to communicate the results of science to end-user groups. Searches were conducted by NERC staff of their database of around 900 ecology projects funded in the previous 8 years for grants evidencing private sector involvement. To be identified by this search, researchers had to have classified their project's focus as being ecology ('population ecology', 'community ecology', 'behavioural ecology' or 'conservation ecology') from within a specified list of possible topic areas and also had to have reported the specific direct or indirect contribution that a private sector partner would make to the research. To assess whether these search criteria were unduly stringent, the authors worked directly with academic researchers who were members of NERC's paid peer reviewing community and asked them to score recent grants they had received to review from NERC for evidence of private sector involvement. This second smaller sample of grants included both successful and unsuccessful proposals submitted to all types of funding programme.

QUESTION-DESIGN WORKSHOPS

We ran workshops in February 2009 with three different business sectors. In each workshop, participants first discussed biodiversity and ecosystem service concepts and reviewed business activities in these areas. Participants then developed a list of 9–10 exemplar questions where they felt ecological research could benefit companies within their sector. Opportunities for and obstacles to research collaboration were also discussed.

We chose three contrasting sectors – mining and quarrying, insurance, and manufacturing, engineering and technology – to ensure a diversity of perspectives. The mining and quarrying sector depends on access to raw materials; manufacturing, engineering and technology companies face both up- and downstream supply chain management issues; and insurance companies create the conditions needed to support the investments of all types of businesses. However, each sector was suggested by the survey of publications and grants as having relatively little existing engagement with the ecological research community, despite being very interested in building such collaborations (see below).

Each workshop involved 11–12 participants. Workshops were restricted to this size to facilitate discussion. Five core participants took part in all three workshops, four from the academic research community (authors PRA, BAE, KJG and TH) and one ecological science advisor from a relevant public agency (JH).

Each workshop included representatives from a suite of companies in the relevant sector (one per company). Individuals from participating companies ranged from the Managing Director to environmental managers. Companies were identified based on recommendations from industry bodies, trade associations and public agencies and through the science team's own informal contact networks. Summary

details regarding participating companies are given in Table 1. These companies were mostly multinational organizations with established CSR programmes, although some specialized operators with a particular interest in biodiversity and ecosystem service topics also participated. The companies therefore do not represent a random sample from within their sector. Innovation surveys commonly involve unrepresentative samples (e.g. Inzelt 2004), because of biased response rates. This may not be a problem for our study, because we seek to identify opportunities for new research collaborations and as such, our sample should be drawn from companies that would be interested in joining such collaborations. The greater representation of large companies also makes sense given concentration profiles in most industries (Scherer & Ross 1990).

Each workshop also involved a representative from a related industry body or trade association (the Mineral Products Association, the Lighthill Risk Network, and EEF, the manufacturers' organization). These individuals provided clarification as to whether the research questions identified would be of interest to other (often smaller) companies from within their sector. Additional representatives from public sector organizations (DEFRA and NERC) participated in some workshops.

Participants were asked to offer personal perspectives in workshop discussions, and their comments may not reflect official positions held by their home organizations. Participants were also offered anonymity for themselves and their employer if appropriate and some chose to remain anonymous; others are included among the authors or recognized in the acknowledgements. Anonymity was offered to satisfy some companies' corporate policies and to allow an open discussion of research priorities and obstacles to collaboration.

QUESTION SELECTION

Business participants were asked to provide initial suggestions for research questions. Most canvassed colleagues from within their home companies to arrive at these suggestions; those representing professional associations and industry bodies canvassed their member companies more broadly. Some participants preferred to suggest questions in the workshops in person rather than providing them in advance as a written list. In total, more than 80 distinct candidate questions were considered in the workshops.

Workshop participants were asked to select from these initial suggestions and to refine question wordings to arrive at a final list of 9–10 questions they felt offered illustrative examples of where applied ecology research would be of interest to their sector. All questions on the initial lists or suggested in person by business participants were considered for inclusion. Several criteria had to be met for a question to be included on the final lists. First, participants had to agree that a question fell within the purview of applied ecological research – some focused instead on issues such as food safety, climatology or improving the energy efficiency of appliances. Academic and public sector

Table 1. Average size of businesses with representatives in each workshop as measured by financial turnover and number of staff

	Mean turnover (UKP)	Mean number of employees
Mining & quarrying	£ 2·1 billion	11·5 k
Insurance	£ 1·3 billion	7·0 k
Manufacturing, engineering and technology	£ 33·1 billion	177 k

participants played an important role in deciding what questions met this first criterion. Next, a question could only be included if one or more business representatives indicated that research directed towards answering it would be of interest to their company. Of questions meeting this criterion, those garnering support from multiple business participants were given greater priority for inclusion. Academic and public sector participants were permitted to suggest questions but these only went forward if business participants indicated they were as important as others on the list. The primary role of academic and public sector participants was to facilitate discussions and to help codify ideas as research questions. They also helped to identify common themes across the workshops.

Results

PUBLICATION AND FUNDING OF RESEARCH ENGAGING WITH BUSINESS

Of the 385 papers reviewed, 15% showed some evidence of private sector involvement. This drops to 10% if we exclude papers where the only evidence of business involvement concerned an environmental consultancy. Of this 10%, the great majority of companies involved in ecological research are connected either to agriculture, fisheries or forestry (Fig. 1). However, the few studies that involved participation of other sectors, such as retail, power generation and telecommunications reveal greater diversity.

The most common ways for businesses to contribute to research were by providing access to land, other assistance in the field or funding (4% of all papers for each type of involve-
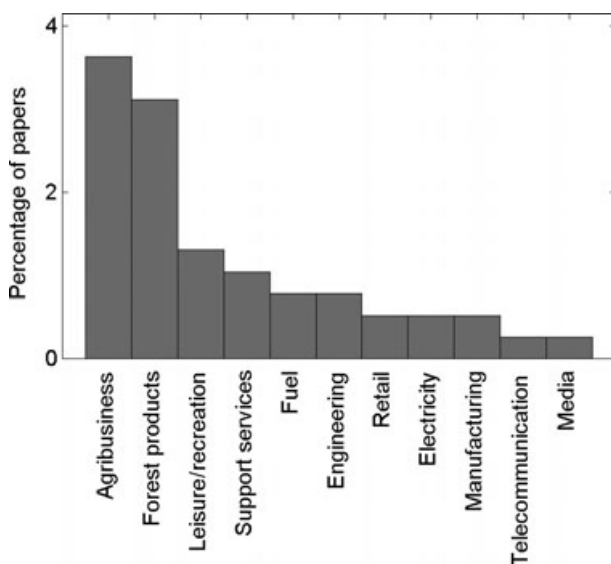

Fig. 1. Percentage of primary research papers published in *Journal of Applied Ecology* or *Ecological Applications* in 2008 that show evidence of involvement of businesses from different sectors (excluding private research institutions and consultancies). Some papers evidence involvement from more than one sector and so categories are non-exclusive. 'Agribusiness' includes fisheries; 'Fuel' includes oil and gas companies as well as companies involved in commercial peat cutting; and Support Services includes companies that support other businesses by providing logistical support, personnel, training, etc.

ment). When collaboration is only at the level of allowing access to land, many collaborative agreements may not be documented in subsequent publications, and so the relevant percentage should be considered an under-estimate. At the same time, where there is only limited evidence of engagement by businesses with the research process (e.g. they provide access to land only), it is unlikely that they see research products as being highly relevant to their operations.

A direct search by NERC staff of their database of around 900 ecology projects funded in the previous 8 years suggested that less than 1% of funded grants had private sector involvement and that the majority of those that did were funded under one of the programmes specifically intended to promote knowledge transfer or exchange with end-users.

In contrast, when NERC's paid peer reviewers examined a sample of 34 submitted grant proposals (including both successful and unsuccessful proposals), they found that 35% of projects made some mention of the private sector. However, more than half of those that did simply identified businesses among a list of potential beneficiaries of the research without providing any suggested delivery model. The remainder proposed particular research products for business end-users, such as presentations or bespoke reports. Only one grant proposal identified a role for businesses in designing research activities. Importantly, none of these more informal end-user engagement mechanisms would have been identified by NERC using the more restrictive database search criterion described above.

EXEMPLAR RESEARCH QUESTIONS FROM DIFFERENT SECTORS

Mining and quarrying: Mining and quarrying operations depend on access to land for exploration and production, sometimes in acutely sensitive areas for biodiversity and ecosystem services (Koziell & Omosa 2003). As such, they often own or manage extensive land holdings of ecological interest. These operations produce variable amounts of non-saleable material, which strongly influences the design and characteristics of quarrying restoration. Operations may also draw on ecosystem services during production (e.g. through the use and movement of water). Guidelines for avoiding and minimizing environmental impacts of operations have been developed from industry best practice in consultation with conservation NGOs (ICMM 2006). Key scientific topic areas concern siting and access decisions, avoiding and minimizing on- and off-site impacts, offsetting any residual impacts with offsite improvements in habitat quality (see Kiesecker *et al.* 2009 for a related example), and progressively restoring sites as phased mineral extraction is completed (Brady & Noske 2009). Restored mines and quarries often provide valuable habitat for many species and have the potential to supply important ecosystem services (e.g. carbon sequestration, flood storage, recreation) that, in some cases, are more highly valued than the pre-operation land use.

Participants in the mining workshop included representatives from companies with a strong national and international presence focused on the extraction of industrial minerals and

aggregates, as well as a professional association representing a sizeable element of the sector in the UK. The exemplar questions identified by these participants were:

1. How do we harmonize ongoing and future planning for biodiversity and ecosystem function with the release of mineral reserves?

2. How do we identify locally and regionally appropriate habitats to restore that will maintain their ecosystem health in the long term in the face of global environmental change?

3. How can we identify ecosystems that are capable of contributing to socioeconomic outputs (for example, through biomass production or supporting sustainable tourism) in addition to ecological function?

4. What are the components of a robust decision matrix that reconciles different (ecological, social and economic) priorities for restoration and post-mining reuse?

5. What is the potential role of restored ecosystems, surface waters, land covers and soils in carbon sequestration, climate regulation and climate change adaptation?

6. How do we define and measure 'success' of restoration efforts in terms of restoring ecosystem function?

7. What are the most cost-effective ecological management methodologies for restoration and post-restoration management of ecosystem function?

8. How long does it take to restore a site to a functioning ecosystem as evidenced, for example, by comparison with semi-natural reference sites?

9. What is required by way of ongoing management and monitoring of restored sites?

10. Where are the overlaps and tensions in biodiversity and broader environmental policies, and can we streamline these policies to ensure greater policy effectiveness at lower regulatory cost?

Site access was identified as providing a possible impediment to expanding research collaborations with the sector. Participants felt businesses would have concerns about allowing field teams access to sites with resources or reserves if there was a risk that the researchers' findings could lead to additional land use constraints. For example, would restrictions on future operations follow if researchers comparing restoration techniques on one part of a site happened across a rare species on a different part of the site? Participants suggested that the prospects for future collaborations would improve if agreements could be put in place that ensured that voluntary participation in a research collaboration would not place businesses at risk from future land use restrictions as a result of the site-specific (as opposed to generalizable) findings of the research study.

Insurance: A functional insurance market is needed to enable the investments that allow other types of business to operate. The insurance sector contains a wide diversity of companies ranging from those that are risk bearing, including both primary insurers and reinsurers, to specialist companies involved in modelling and understanding risk or providing customer support. Risk identification and quantification is an important preliminary to an insurer's decision on whether, and / or where to provide cover and at what price. Measurement of risks is typically based on a combination of observed historical losses

and physically or statistically-based models; it needs to include a measurement of the potential frequency and intensity of those losses. This assessment requires an understanding of the hazard, the exposed assets at risk and their vulnerability to the behaviour of the hazard at a given location, normally expressed in terms of some form of monetary loss potential. The need for diversification of risk requires exposures to be distributed sufficiently independently across a portfolio of places and/or insured activities in relation to the hazards being considered.

The pace of environmental change presents particular challenges to insurers, because of the emergence of novel environmental risks, such as those caused by the changing climate (Mills 2009), emerging diseases, new pollutants, and invasive species. New environmental regulations themselves bring new risks and liabilities to businesses that must be insured. For example, the EU Environmental Liabilities Directive (EU 2004) allows businesses to be held financially responsible for damages that arise from their operations to land and water resources and to species and habitats of conservation concern. Specialist insurance companies already provide insurance cover for well-commoditised ecosystem goods and services, such as agricultural and timber products. Some leading companies are looking beyond these products to assess whether new types of insurance are needed to support investments in emerging ecological commodities (Pearce 2002), such as carbon offsets, biodiversity offsets or benefit flows from ecosystem services.

Participants in the insurance workshop included representatives from insurers, re-insurers, global insurance intermediaries, research groups focussed on insurance risk assessment, and an NGO focused on promoting dialogue between the insurance sector and academic researchers. Exemplar questions identified by participants to illustrate where additional ecological research would help the industry were:

11. What earth observation data are available to generate better estimates of insurance risks, and can we do more to translate these data from their existing environmental science applications to this context? For example, the industry currently relies on spot loss data when looking to insure against forestry losses. Can we estimate more accurate risk profiles for forestry projects on a global scale by integrating spatially resolved satellite data on burn scars?

12. How does vegetation (including species, age and other characteristics of individual trees) change subsidence risk for buildings and can we capture that in risk modelling?

13. Where can we make better use of long-term ecological records (e.g. peat cores, sediment records, tree rings, historical documents) to identify levels of baseline variability and non-stationarity in time series of potential environmental risks and hazards and can we use these records to make causal association with past events?

14. How do we map, model and attribute the contaminant sources that might spread in a flooding event? Can we identify better land use or management measures to mitigate such possible spread?

15. How can we quantify the uncertainty in value estimates of ecosystem services or biodiversity losses associated with a

catastrophic event in a way that reflects spatial and temporal variation in the underlying ecological mechanisms and ecosystem functions that support these?

16. When do land use and habitat changes adjacent to urban areas increase fire, flood or other risks through contagion effects?

17. What data are available from ecological mitigation projects (e.g. for habitat creation, carbon sequestration or water purification) that could be used to create a risk profile (frequency, severity and cause of losses) for such projects? In the absence of such data, what other means can be used to develop such a risk profile?

18. How have land use and climate change altered the risks of latent disease, e.g. through changing the rate of human contact with disease reservoirs in other species?

19. How do we attribute sources of contamination from accidental release of genetically modified organisms and model their potential spatial transfer and long-term impacts?

More generally, the need for horizon scanning exercises that combine expertise from the ecological research community with industry representatives to identify emerging ecological risks was highlighted. Participants also stressed the need for ecological researchers to engage in new types of interdisciplinary collaboration. For example, collaborations between researchers in ecology and legal scholars are needed to determine when ecological evidence will be sufficient to attribute liability in a court of law.

Manufacturing, engineering and technology: With evolving regulations, societal preferences and the corporate social responsibility agenda, manufacturing companies are increasingly looking for ways to identify and address the broader environmental impacts of their products and operations. This requires consideration of where inputs and materials are sourced and what impacts are involved in supplying them, what processes are involved in production and what is the likely fate of products after they have fulfilled their useful life. This can be particularly challenging when developing new technologies for which the potential long-term environmental impacts may be poorly understood.

Participants in the workshop with manufacturing, engineering and technology companies included major multinational companies heavily invested in the development of new technologies as well as a related business association. The exemplar questions identified were:

20. How can we trace and capitalize better upon the contribution ecosystems make to product value (e.g. through access to quality raw materials and processes at low cost)? For example, with what accuracy can we assess the contribution of upstream habitats to improving the supply of freshwater to semiconductor plants where large quantities of clean water are needed in chip production?

21. In evaluating the long-term impacts of future products, how can we factor in impacts on the environment more broadly to include biodiversity and ecosystem services? For example, when working with businesses designing technologies for the tidal renewables industry, with what degree of confidence can we predict the impacts that new products will have on marine ecosystems and biodiversity?

22. How can we design or adapt spatial planning tools for ecosystem services and biodiversity so that they can support facility location, design and operation choices that will maximize benefits to operations from the environment, while minimizing environmental impacts or even making net environmental gains?

23. To what extent can we ameliorate environmental impacts of products through choices over where and when they are deployed given variation in ecosystem dynamics and variation in the vulnerability of ecosystems? For example, can we account better for spatial and temporal variation in air pollution vulnerability across ecosystems when evaluating product performance?

24. Can we forecast future supplies of raw materials (including water, land, and energy supplies, as well as metal and mineral resources) taking into consideration the trade-offs that must be confronted when extracting those materials with impacts on other environmental goods and services?

25. How can a consideration of ecosystem goods and services help inform planning for secure and sustainable supply chains in the face of a changing climate, changing societal preferences regarding the environment, etc.?

26. How do we factor ecosystem impacts into life cycle analysis and footprinting techniques for current products and new substitutes (e.g. oil palm)? Do current metrics adequately capture the full breadth of ecosystem impacts? What other metrics are needed to capture those?

27. How can businesses capitalize on the well-being benefits provided to existing employees and local communities by ecosystems and the environment (including air quality, biodiversity, and access to ecosystem services) and also use these to achieve competitive advantage in recruitment?

28. How can we develop a low-cost, rapid assessment approach to enable more businesses to capitalize on the opportunities provided to them by ecosystem services and to engage with environmental reporting and environmental risk and opportunity management?

In the more general discussion, participants noted that the list of research questions might look different if repeating the exercise with companies from other manufacturing sectors or small and medium sized enterprises.

Discussion

Businesses will make new scientific demands of researchers in applied ecology as they seek to exploit new opportunities presented by biodiversity and ecosystem services and to grow their contribution to efforts to manage human impacts on the natural world. We used peer reviewed publications to provide one measure of how researchers in applied ecology were currently meeting such demands, applications for research grants to infer the role government research councils play in funding such collaborations, and workshop activities with businesses from three different sectors to scope opportunities for expanding collaborations.

Of the surveyed papers, only 10–15% evidenced business involvement. These collaborations were dominated by traditional rural industries with which applied ecology research has had a long association (agriculture, fisheries and forestry). Moreover, the nature of these collaborations (e.g. land access) often did not suggest a strong engagement of businesses with the research process. This survey of journal publications suggests that new knowledge production derived from existing collaborations between applied ecology researchers and businesses is limited.

Publications provide the most commonly used metric of research productivity in science - the 'fundamental currency' as one author put it (Kennedy 1997, pp. 186). However, collaborations between researchers and businesses take many forms and whatever indicators one uses to measure them, some collaborative activities are likely to be missed. For example, we could instead have measured contract research activity, but contract research represents a particularly advanced type of business-research interaction (Inzelt 2004) and this measure would miss many other types of interaction (Martinelli, Meyer & von Tunzelmann 2008). One particular concern about using a publication-based metric is that those who produce knowledge that is of greatest interest to businesses will look to appropriate that knowledge through patents instead of publishing it. However, the available evidence suggests to the contrary that researchers responsible for most patents tend to be the most prolific publishers of research findings (Van Looy, Callaert & Debackere 2006). Furthermore, biodiversity and ecosystem services are partly public goods and financial benefits from patenting many ecological research findings will be limited. A second concern is that much reporting of the results of business-research collaborations in applied ecology happens through other outlets, including industry and NGO publications and websites (e.g. International Council on Mining and Metals [ICMM] 2006; http://www.ecosystem marketplace.com; http://www.iucn.org/about/work/program mes/business). Such outlets communicate research findings to the business community in ways that scientific journals cannot. Indeed, workshop participants commented that publication of results in subscription-only journals impedes engagement with the business community. We would welcome further attempts to quantify the productivity of collaborations between businesses and the ecological research community by monitoring non-peer reviewed outputs. At present, we are aware of no alternative estimates of the extent of collaborations between businesses and researchers in applied ecology to compare with those that we present.

We examined grants submitted to a UK science funding agency as an example of how governments support efforts to engage businesses in applied ecology research. These were responsive mode grants (researchers were free to choose the research topic area) and included proposals for programmes specifically designed to engage end-users with research. We found similar issues regarding how collaborative research activity is measured and reported. The funding agency's own database indicates very limited research activity involving the private sector (< 1% of grants). However, this probably reflects rather stringent criteria for research to qualify as engaging with businesses in some way, because a direct examination of a smaller sample of research grants submitted to the same funding agency revealed a higher percentage of researchers gave some thought to potential business end-users of research. However, most proposals lacked clear plans for how the researchers would engage with or communicate results to relevant businesses.

Two economic benefits to society justify public investment in research when considering goods that fall partly outside the market economy (Fischer 2008), like many ecosystem services. First, because knowledge itself has public good properties, private research investment alone would lead to less investment in research than would be socially desirable (Arrow 1962). Second, even in the hypothetical situation where knowledge externalities could be overcome, it would still be worth society investing in such research, because private innovators could not appropriate the social benefits derived from environmental goods. Public investments that promote science-business collaborations includes research grants to scientists, but also tax breaks for businesses' investments in research and development (Inzelt 2004) and support for intermediaries that aid communication between the two communities (Howells 2006). A fuller accounting of public investment in collaborations between applied ecology researchers and businesses would also account for these latter two mechanisms.

We ran workshops with businesses from three different sectors to explore the types of ecological research questions that businesses would find useful. Unlike previous studies (Sutherland *et al.* 2006, 2008, 2009; Morton *et al.* 2009), we do not claim the lists present the most important research questions for each sector. Rather participants were charged to identify questions that could serve as exemplars to communicate to researchers in ecology how their science could be useful to businesses. Full prioritization of the questions would require exhaustive canvassing of businesses. However, the nascent nature of discussions between ecological researchers and businesses means that any such attempt probably would have suffered from communication problems and low response rates and, as a result, would have failed to obtain the representative samples needed. This project was conducted during an acute economic downturn, meaning the inevitable bias towards businesses that are the 'best in class' on biodiversity and ecosystem service issues would only have been accentuated. Despite these shortcomings, we believe that the question lists that we were able to produce provide some insights into the types of ecological research topic businesses would find useful.

The questions demonstrated considerable interest in the business community about biodiversity and ecosystem services. The diversity of questions reflects our decision to target three very different sectors, although some common questions are apparent between sectors (e.g. Q1, Q24). A number of the questions are concerned with managing costs arising from the impacts of business operations on ecosystems (e.g. Q7, Q23), while others

would help businesses exploit new opportunities that arise from biodiversity and ecosystem services (e.g. Q17, Q27). Some questions are targeted towards helping businesses to plan for the long-term (e.g. Q21), while the answers to other questions would lend themselves to more immediate commercial applications (e.g. Q12). If successful collaborations are to develop, the ecological research community needs to develop a better understanding of these and other motivations of businesses.

Questions related to ecosystem services are common in the lists. Discussions regarding the importance of, and opportunities provided by, ecosystem services are often more interesting to businesses than discussions of the need to conserve biodiversity for its own sake (MEA 2005; Armsworth *et al.* 2007). For example, in the workshop focused on the research needs of mining and quarrying companies, there was clear agreement among business participants that priority research needs for the sector should move beyond biodiversity to look at how ecosystems function and the delivery of ecosystem services. Interestingly, this was because the business representatives already felt their companies had well-established programmes in place for managing their impacts on biodiversity and felt that the knowledge base within the industry about how to restore land for biodiversity was, on the whole, reasonably well-advanced. However, there were strong appeals for hands-on techniques for restoring, monitoring and managing sites in a way that takes into account the need to support ecosystem functions and ecosystem services.

As with previous question design exercises (Sutherland *et al.* 2006, 2008, 2009; Morton *et al.* 2009), the final question list was influenced by interpretations of definitions. We decided some questions showed too little connection to applied ecology for inclusion; yet we included questions regarding ecosystem services, despite their interdisciplinarity. Indeed, business participants were in agreement across all three workshops that research would need to become more interdisciplinary to see greater uptake by the business community. Other definitional issues also influenced the question lists. In workshop discussions, business participants sometimes struggled to distinguish between the conservation movement in general, regulatory agencies and the ecological research community. This confusion may reflect the fact that one important role ecological science has to play is in enabling and supporting conversations between businesses and regulators or between businesses and the wider conservation community. For example, some research questions suggested by businesses were directed towards streamlining policies and improving policy effectiveness both in general (e.g. Q10) and specifically through changes to land use planning (e.g. Q4, Q14). Business participants also highlighted a role for more direct public funding in carrying forward research ideas to application by supporting the delivery and longer term management of biodiversity benefits and ecosystem services.

A common theme across the discussions was that the data needed to answer many key questions may already be held within the science community or within the business sectors themselves. For example, participants in the mining and quarrying discussion felt that much could be learned from meta-analyses that look for common trends across the many Environmental Impact Assessments published by the industry. In the discussions with the insurers, participants often felt that the required ecological data already existed but were not being communicated to this constituency or analysed in the most useful ways.

The long time delay between when research activities are initiated and when they deliver results proved an impediment to discussions with some businesses. These businesses were focused on current CSR challenges associated with reducing their greenhouse gas emissions and struggled to forecast the ecological research they would be likely to need in 5–10 years time. Others remarked that the existing time-scales involved in bringing academic research to fruition were not compatible with the rate of turnover of staff in many businesses in light of reorganizations, mergers, closures, etc. That being said, some participants (e.g. all of those associated with mining and quarrying) did not consider the slow rate of progress that accompanies academic research an impediment to collaborations, because their companies' business plans already operate over decadal time-scales.

Conclusion

In light of the potential for the business community to contribute to efforts to stem the loss of biodiversity and ensure better management of ecosystem services, the dialogue between conservation groups and business has shifted from one of opposition towards one of partnerships (Rose 2000). Research in applied ecology has a critical role to play in allowing partnerships like this to grow and succeed. However, publications in leading journals and grant applications to a relevant research council reveal only limited collaborations between researchers in applied ecology and businesses, collaborations that rarely look outside the traditional constituencies of farming, forestry and fisheries. Applied ecological research will enjoy much greater application if it also tries to connect with other business sectors. Discussions with three very different sectors make clear that there are rich veins of scientific inquiry that would shed light on fundamental ecological processes while also having important implications for businesses.

References

Armsworth, P.R., Chan, K.M.A., Daily, G.C., Ehrlich, P.R., Kremen, C., Ricketts, T.H. & Sanjayan, M.A. (2007) Ecosystem service science and the way forward for conservation. *Conservation Biology*, **21**, 1383–1384.

Arrow, K.J. (1962) Economic welfare and the allocation of resources for invention. *The Rate and Direction of Inventive Activity: Economic and Social Factors.* Universities-National Bureau Committee for Economic Research, pp. 609–625.

Belkhodja, O. & Landry, R. (2007) The Triple-Helix collaboration: why do researchers collaborate with industry and the government? *What are the factors that influence the perceived barriers? Scientometrics*, **70**, 301–332.

Brady, C.J. & Noske, R.A. (2009) Succession in bird and plant communities over a 24-year chronosequence of mine rehabilitation in the Australian monsoon tropics. *Restoration Ecology*, in press. doi:10.1111/j.1526-100X.2008.00511.x.

Daily, G.C. & Ellison, K. (2002) *The New Economy of Nature: the Quest to Make Conservation Profitable*. Island Press, Washington.

Dasgupta, P. & David, P.A. (1994) Towards a new economics of science. *Research Policy*, **23**, 487–521.

Etzkowitz, H. (2008) *The Triple Helix: University-Industry-Government Innovation in Action*. Routledge, New York, NY.

European Union [EU] (2004) Directive 2004/35/CE of the European Parliament and of the Council of 21 April 2004 on environmental liability with regard to the prevention and remedying of environmental damage. *Official Journal of the European Union*, **143**, 56–75.

Fischer, C. (2008) Emissions pricing, spillovers, and public investment in environmentally friendly technologies. *Energy Economics*, **30**, 487–502.

Howells, J. (2006) Intermediation and the role of intermediaries in innovation. *Research Policy*, **35**, 715–728.

International Council on Mining and Metals [ICMM] (2006) *Good Practice Guidance for Mining and Biodiversity*. ICMM, London.

Inzelt, A. (2004) The evolution of university-industry-government relationships during transition. *Research Policy*, **33**, 975–995.

Jeurissen, R. & Keijzers, G. (2004) Future generations and business ethics. *Business Ethics Quarterly*, **14**, 47–69.

Kennedy, D. (1997) *Academic Duty*. Harvard University Press, Cambridge, MA.

Kiesecker, J.M., Copeland, H., Pocewicz, A., Nibbelink, N., McKenney, B., Dahlke, J., Holloran, M. & Stroud, D. (2009) A framework for implementing biodiversity offsets: selecting sites and determining scale. *BioScience*, **59**, 77–84.

Koziell, I. & Omosa, E. (2003) *Room to Manoeuvre? Mining, Biodiversity and Protected Areas*. International Institute for Environment and Development and WBCSD. IIED, London.

Kruss, G. (2008) Balancing old and new organizational forms: changing dynamics of government, industry and university interaction in South Africa. *Technology Analysis & Strategic Management*, **20**, 667–682.

Lovins, A.B., Lovins, L.H. & Hawken, P. (1999) A road map for natural capitalism. *Harvard Business Review*, **77**, 146–158.

Martinelli, A., Meyer, M. & von Tunzelmann, N. (2008) Becoming an entrepreneurial university? A case study of knowledge exchange relationships and faculty attitudes in a medium-sized, research-oriented university. *Journal of Technology Transfer*, **33**, 259–283.

Millennium Ecosystem Assessment, Business and Industry Synthesis Panel [MEA] (2005) *Ecosystems and Human Well-being: Opportunities and Challenges for Business and Industry*. World Resources Institute, Washington, DC.

Mills, E. (2009) A global review of insurance industry responses to climate change. *Geneva Papers on Risk and Insurance: Issues and Practice*, **34**, 323–359.

Morton, S.R., Hoegh-Guldberg, O., Lindenmayer, D.B., Harriss Olson, M., Hughes, L., McCulloch, M.T. *et al.* (2009) The big ecological questions inhibiting effective environmental management in Australia. *Austral Ecology*, **34**, 1–9.

Nowotny, H., Scott, P. & Gibbons, M. (2003) 'Mode 2' revisited: the new production of knowledge. *Minerva*, **41**, 179–194.

Pearce, D. (2002) *The Insurance Industry and the Conservation of Biological Diversity: An Analysis of the Prospects for Market Creation*. Organisation for Economic Co-operation and Development, Environmental Policy Committee, Paris.

Rose, M. (2000) Business and biodiversity – a mutually profitable partnership. *Oryx*, **34**, 83–84.

Rubino, M.C. (2000) Biodiversity finance. *International Affairs*, **76**, 223–240.

Scherer, F.M. & Ross, D. (1990) *Industrial Market Structure and Economic Performance*. Houghton Mifflin, Boston, MA.

Sutherland, W.J., Armstrong-Brown, S., Armsworth, P.R., Brereton, T., Brickland, J., Campbell, C.D. *et al.* (2006) The identification of one hundred ecological questions of high policy relevance in the UK. *Journal of Applied Ecology*, **43**, 617–627.

Sutherland, W.J., Bailey, M.J., Bainbridge, I.P., Brereton, T., Dick, J.T.A., Drewitt, J. *et al.* (2008) Future novel threats and opportunities facing UK biodiversity identified by horizon scanning. *Journal of Applied Ecology*, **45**, 821–833.

Sutherland, W.J., Adams, W.M., Aronson, R.B., Aveling, R., Blackburn, T.M., Broad, S. *et al.* (2009) One hundred questions of importance to the conservation of global biological diversity. *Conservation Biology*, **23**, 557–567.

Van Looy, B., Callaert, J. & Debackere, K. (2006) Publication and patent behavior of academic researchers: conflicting, reinforcing or merely co-existing? *Research Policy*, **35**, 596–608.