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Integrating Science and Policy: A Case Study of the Hubbard Brook Research Foundation Science Links Program

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Scientists, related professionals, and the public have for decades called for greater interaction among scientists, policymakers, and the media to address contemporary environmental challenges. Practical examples of effective "real-world" programs designed to catalyze interactions and provide relevant science are few. Existing successful models can be used, however, to develop and expand the work of integrating, synthesizing, and communicating ecosystem science for environmental policy and natural-resource management. We provide an overview of the structure and strategies used in the Hubbard Brook Research Foundation Science Links program, now in its thirteenth year as a successful boundary-spanning organization. We detail project activities and results and share lessons and challenges for the further advancement of Science Links and other efforts to bridge the science–policy divide. Furthermore, we suggest greater emphasis in boundary-spanning programs as a part of publicly funded research initiatives and as legitimate scholarly endeavors that support the scaled coproduction of knowledge and that harness scientific research to support informed policy and environmental management.

Keywords: interaction of scientists, integrating science and policy, environmental challenges, science communication, boundary-spanning programs

Science has long played an important role in issues of national significance such as health and medicine, space exploration, energy production, and national defense. Popular support and funding for science from World War II through the 1960s was predicated on the belief that investments in basic research—in fundamental scientific understanding—would yield beneficial outcomes for society through the passive flow of information to applied technologies (Pielke 2007). By the 1990s, scientists and decisionmakers began to question whether this conventional approach was adequate to meet the pressing problems of the times, such as human-accelerated environmental change manifested by climate disruption, species extinction, deforestation, altered global nitrogen cycles, accumulation of toxins, and other large-scale disturbances (Lubchenco 1998, Cash et al. 2003, Palmer et al. 2005, Pouyat et al. 2010).

Despite the growing call for effective scientific engagement in public policy (NSF 2002, Palmer et al. 2005), few innovative programs and structures exist in the ecological sciences that support efforts at the interface of science and policy (Palmer et al. 2005, Clark 2009). We present the Hubbard Brook Research Foundation (HBRF) Science Links program as one effective model for integrating complex ecosystem science and environmental policy through synthesis, distillation, feedback, and outreach. We propose that funding agencies and leading academic and scientific institutions should initiate, catalyze, support, and invest in new programs aimed at expanding our national capacity for harnessing scientific research as a resource—and, indeed, the underpinning—for environmental policymaking and resource management.

HBRF and the Futures Assessment Project

HBRF is a nonprofit 501(c)(3) organization, founded in 1993 to provide sustained leadership and support to the Hubbard Brook Ecosystem Study (HBES) and to develop new initiatives linking ecosystem science and public policy. HBES is a long-term multidisciplinary, multi-institutional research program designed to study the structure, function, and development of forests and interconnected aquatic ecosystems (Likens and Bormann 1995, Groffman et al. 2004). Established in 1963, HBES is known for its influential role in identifying and addressing acid rain and its effects on forest ecosystems in North America, as well as in pioneering the use of the small watershed as a unit of ecosystem study.

HBRF launched the Futures Assessment Project in 1996 to investigate the gap between science and policy

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by reviewing existing literature, analyzing case studies, and conducting interviews with scientists, policymakers, and natural-resource managers. This assessment affirmed the view that ecosystem science is often underutilized in conservation and environmental policy. The assessment concluded that the disconnect between scientific information and policy decisions stems in part from poor access to research findings, the lack of constructive engagement for scientists in the policy process and vice versa, and a paucity of published literature that is relevant to policy needs. In 1998, HBRF initiated the Science Links program to address these challenges. The overarching goal of Science Links is to provide an interface between science and policy by supplying information on the likely ecosystem consequences of policy actions that is credible, salient, and legitimate (after Cash et al. 2003 and Clark et al. 2006) and by ensuring that this information is timely, compatible, and widely accessible to information users (after Jones et al. 1999). Science Links does not advocate for specific policy outcomes.

Science Links: Synthesis, distillation, and outreach

The importance of interface organizations that explicitly take on boundary-spanning functions such as stakeholder engagement, communication, translation, and mediation has been highlighted in the literature (Cash et al. 2003, McNie 2007, Osmond et al. 2010). Here, we discuss the Science Links approach to boundary spanning through three key functions: policy-relevant synthesis, the distillation of results, and outreach.

Policy-relevant synthesis. The Science Links approach is based on the understanding that the impact of science on environmental policy and management is impeded, in part, by the fragmentation of knowledge as it is published in the scientific literature (Clark 2009). Although individual studies are crucial for the advancement of science, they often do not include relevant information or information explicit enough to guide policy decisions. The synthesis of existing knowledge in the context of specific policy options is a need that often goes unmet. To address this issue, HBRF produced a series of synthesis articles related to air pollution and its effects on the structure and function of forest and aquatic ecosystems in the northeastern United States (Driscoll et al. 2001a, 2003a, 2007a). We focused on changes in the cycling of sulfur, nitrogen, and mercury, using decades of research from the HBES, national monitoring programs (e.g., the National Atmospheric Deposition Program) and from other studies in the region. The synthesis articles were developed in parallel with several key policy deliberations at the state, regional, and federal levels, including proposed climate legislation and multipollutant bills to address sulfur dioxide, nitrogen oxides, and mercury emissions and ozone formation; assessment of the effectiveness of the Clean Air Act; consideration of secondary air-quality standards to protect public welfare (NRC 2004); New Source Review cases to limit emissions from older electric utilities (figure 1, box 1); and the development of total maximum daily loads (TMDLs) to improve the quality of impaired surface waters.

To develop the synthesis articles and to ensure their policy relevance, HBRF convened teams of 10 to 12 scientists and 4 to 6 policy advisers. The scientists were selected on the basis of the need for disciplinary coverage and to represent a diversity of ideas. The policy advisers were selected by the lead scientist and the HBRF executive director, with the objective of including representatives from state and federal agencies that address both air and water resources and who

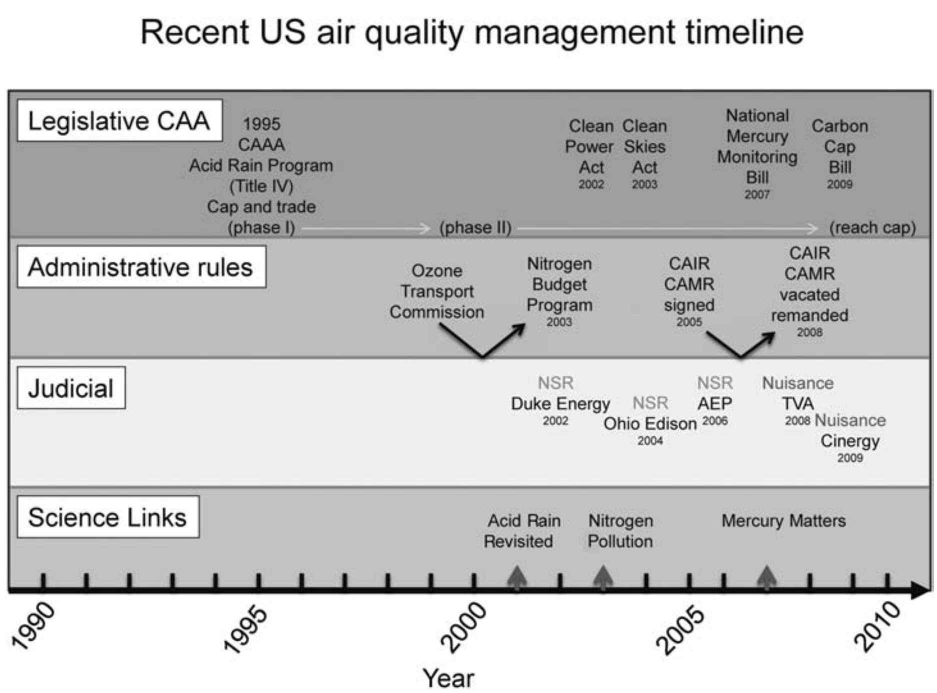


Figure 1. Time line of legislative, administrative, and judicial actions pertaining to air quality management in the United States and the release of Science Links projects pertaining to air pollution. This time line largely reflects federal initiatives, although states participated in New Source Review (NSR) cases, and the Tennessee Valley Authority (TVA) nuisance case was initiated by North Carolina. Abbreviations: AEP, American Electric Power; CAA, Clean Air Act; CAAA, CAA Amendments; CAIR, Clean Air Interstate Rule; CAMR, Clean Air Mercury Rule.

Box 1. Science Links projects and their impact at a glance.

Following the 1990 Amendments of the Clean Air Act, there were marked decreases in US emissions of sulfur dioxide. As a result, there was a widespread assumption that the problem of acid rain was over (figure 1). However, new science emerged in the late 1990s to show that despite these emission controls, affected surface waters were slow to recover (Stoddard et al. 1999); soil acidification was continuing (Likens et al. 1996), with linked effects on red spruce (DeHayes et al. 1999) and sugar maple (Horsley et al. 2000); and there were far-reaching effects of elevated atmospheric nitrogen deposition. Acidification model calculations were consistent with these observations and indicated that additional emission controls would be needed: the greater the decreases in emissions, the greater and faster the ecosystem recovery. Nitrogen mass balance model calculations showed that atmospheric deposited nitrogen was a substantial fraction of the total nitrogen inputs to large coastal basins in the eastern United States (Castro et al. 2003).

These messages were communicated through the Acid Rain Revisited (Driscoll et al. 2001b) and Nitrogen Pollution (Driscoll et al. 2003b) projects. This synthesis and outreach supported the need for further emissions controls, which were considered through legislative bills (Clean Power Act, Clean Skies Act) and administrative rules (Nitrogen Budget Program, Clean Air Interstate Rule), and helped inform legal activities involving the US Department of Justice and the states concerning the ecosystem effects of air pollution (figure 1). In the Nitrogen Pollution project, HBRF partnered with others to develop a series of peer-reviewed articles on the effects of elevated inputs of nitrogen on ecosystems at the regional and the global scale (Aber et al. 2003, Driscoll et al. 2003a, Fenn et al. 2003a, 2003b, Galloway et al. 2003). Both the Acid Rain Revisited project and the Nitrogen Pollution project were highly influential in the National Research Council (NRC 2004) report on air quality management in the United States. The National Research Council (2004) report did much to focus attention on the multimedia aspects of air pollution, the importance of emissions of reduced nitrogen (e.g., ammonia) in air quality issues, and the need to develop secondary standards that are suitable to address the public welfare aspects of air pollution, manifested through effects on ecosystem structure and function.

The Mercury Matters project was a synthesis of the ecological effects of mercury emissions to the atmosphere, including the sources and deposition of atmospheric mercury, the transport of mercury through watersheds and the production of methyl mercury, and the trophic transfer and exposure of this methyl mercury in freshwater ecosystems (Driscoll et al. 2007b). The Mercury Matters project was particularly relevant to air policy, because, at the time, the EPA was considering the Clean Air Mercury Rule (CAMR). The CAMR was a cap-and-trade program directed at mercury emissions from electric utilities. The Science Links analysis demonstrated the occurrence of biological mercury hotspots and the connection between emissions from local and regional sources and the potential for local mercury deposition. Through this work, the appropriateness of the mercury-trading program was questioned (Evers and Driscoll 2007, Evers et al. 2007). The CAMR was vacated by the Circuit Court of Appeals for the District of Columbia in 2005. Subsequent US House and Senate bills (H.R. 1533 and S. 1183) to establish a national mercury-monitoring network cited the findings from this work.

had extensive experience and seniority within their agencies. The representatives were recruited directly by the lead scientist through personal outreach and were sent a follow-up letter outlining the goals, time line, and outcomes of the project, with a description of the specific role and duties of a policy adviser. The policy advisers helped to frame the initial questions for the synthesis, to ensure that the synthesis remained relevant to policy, and to link the results to specific measurable policy goals and strategies. The teams were supported by HBRF staff, who were responsible for designing and managing stakeholder engagement processes, analyzing policy linkages, translating and distilling results for broader audiences, and convening outreach activities. In addition, HBRF supported a PhD-level research fellow for each project who coordinated data collection, analysis, and modeling (figure 2). The research that underpins the synthesis efforts has been supported largely through National Science Foundation (NSF) grants, including grants from the Long Term Ecological Research (LTER) program. Science Links activities were supported entirely through grants from private foundations on the basis of proposals developed by HBRF and through modest individual donations.

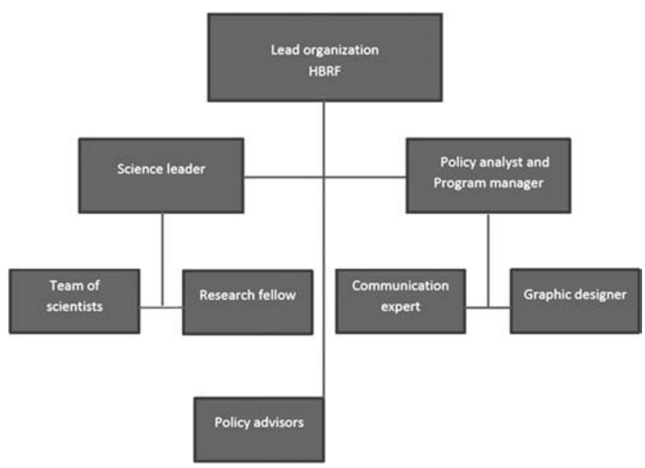


Figure 2. Structure of the Hubbard Brook Research Foundation (HBRF) Science Links projects balances stakeholder involvement with scientific synthesis efforts and provides staffing to support comprehensive policy analysis, modeling, and communications.

The Science Links projects for sulfur (Acid Rain Revisited), nitrogen (Nitrogen Pollution: From the Sources to the Sea), and mercury (Mercury Matters) have been completed, and updates and further outreach are ongoing. A carbon Science Links project is nearing completion. Science Links projects typically take three to four years to complete (figure 3).

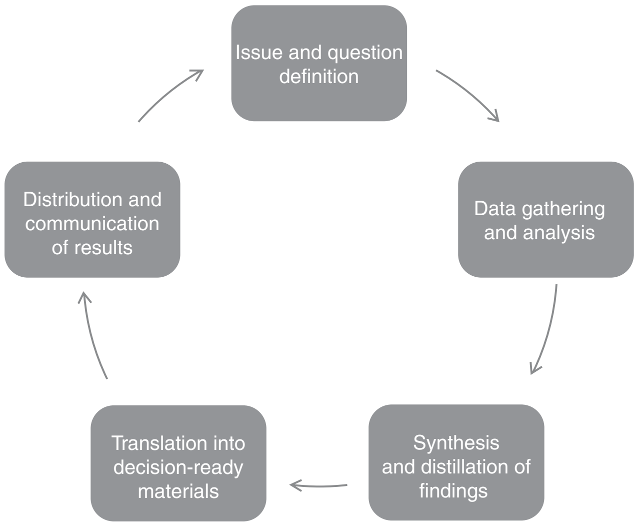


Figure 3. Simplified Science Links cycle showing the major phases of the typical three- to four-year project. At each phase, scientists and decisionmakers consult on the specific approaches and needs for spanning the boundary between emerging science and current policy and management decisions.

The synthesis articles were authored by the members of the science team and the Science Links project manager and were published in peer-reviewed journals. The final articles reflect a consensus view of the science team.

In each article, the state of the science related to the sources and effects of air pollutants was assessed, the likely environmental response and potential unintended consequences to specific policy options were analyzed, and larger ecosystem concepts that are also relevant to policy and management were advanced. Whenever it was possible, the synthesis was based on long-term observations and spatially explicit regional data. Peer-reviewed quantitative models were used to evaluate the potential consequences of defined policy scenarios, such as the PnET-BGC model (*www.ecs.syr.edu/faculty/driscoll/personal/PnET%20BGC.asp*; Gbondo-Tugbawa et al. 2001), the Watershed Assessment Tool for Evaluating Reductions Strategies for Nitrogen (Whitall et al. 2004), and the ISCST3 model (Han et al. 2008).

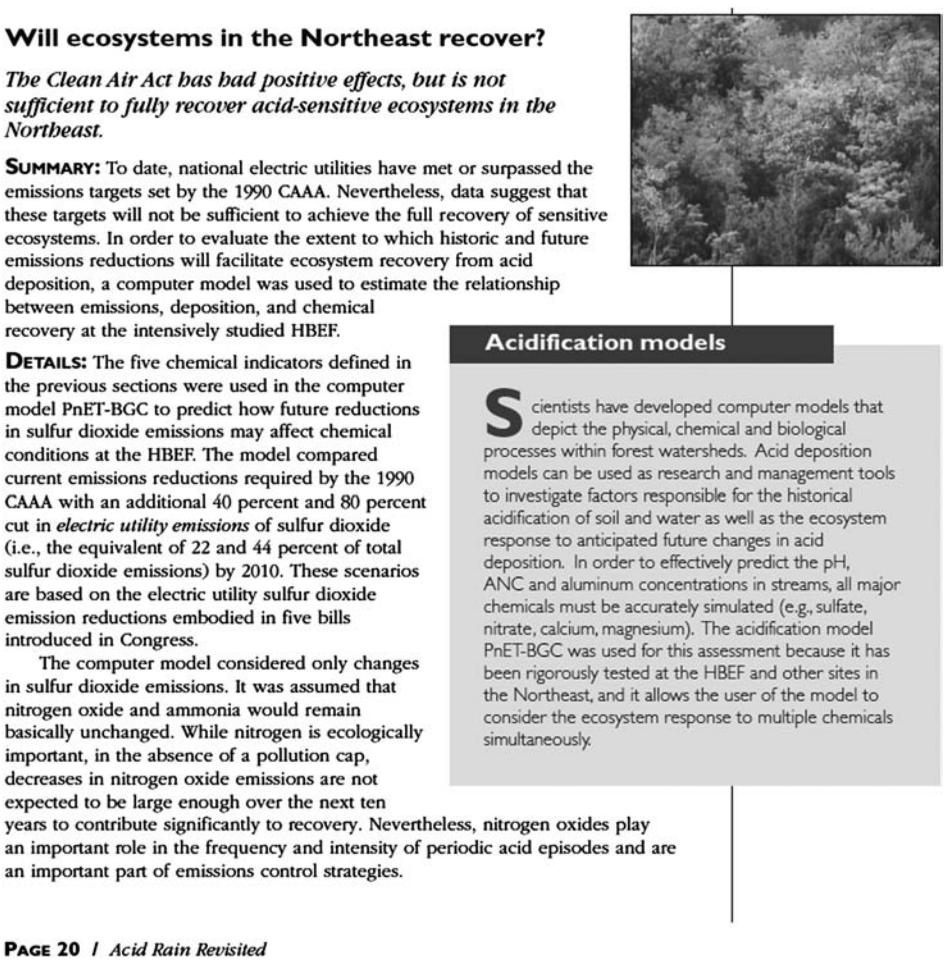
For each project, the Science Links team framed the outputs of the models in terms of environmental endpoints and consequences that had policy significance, determined on the basis of input from policy advisers. For example, in the Acid Rain Revisited project, we modeled the likelihood of surface water recovery as measured by specific chemical thresholds under a range of sulfur and nitrogen oxide emissions and deposition scenarios that were linked to specific legislative proposals (Driscoll et al. 2001a). For the Nitrogen Pollution project, a watershed nitrogen mass balance model was used to quantify the relative contribution of nitrogen sources, such as atmospheric deposition, wastewater effluent, and nonpoint runoff, and to evaluate various mitigation options for these sources. Thus, modeling served as a tool for informing the development of TMDLs and associated management strategies for several major Northeast basins (Driscoll et al. 2003a, Whitall et al. 2004). For the Mercury Matters project, a spatial analysis was conducted to quantify biological mercury hotspots using human-health and wildlife-health criteria for mercury in fish tissue and to model the contribution of local sources to mercury deposition in order to evaluate the potential consequences of proposed rules for trading mercury emissions (Driscoll et al. 2007a, Han et al. 2008).

For those data sets and modeling efforts that were site specific, we used spatial observations and extrapolations to present the results in a regional context so that information from intensive-study sites would better serve the information needs of policymakers. For instance, in the analysis of acid rain effects, surface water survey data from New England were used to regionalize a model scenario analysis conducted for the HBEF.

Each synthesis article concluded with a discussion of the implications of the results for the larger ecosystem concepts relevant for decisionmakers, including the timing and processes of environmental recovery (Driscoll et al. 2001a), the confounding effects of multiple stressors (Driscoll et al. 2003a), the importance of local versus global emissions sources (Driscoll et al. 2007a, Han et al. 2008), and biological hotspots associated with mercury deposition (Driscoll et al. 2007a, Evers et al. 2007).

Distillation of results. Effective science outreach and communication is critical if we are to improve environmental decisionmaking (Lubchenco 1998, Bennett et al. 2005, Gropp 2006). To help meet this need, HBRF published supporting Science Links reports that distilled the results of the peer-reviewed publications for decisionmakers (Driscoll et al. 2001b, 2003b, 2007b). These "translation" reports are arguably the most important, far-reaching output of the Science Links projects for policymakers, educators, and the general public. Because the Science Links projects discussed here were focused on informing regional and federal policy issues (distinct from changing individual behavior or motivating local action), the primary audiences for these reports were congressional staff and state and federal agency personnel directly involved in the development, implementation, and assessment of environmental rules and regulations. However, these reports have also been effective in communicating findings to the media, the scientific community, and science educators. In fact, interest among educators led HBRF to create a supplemental teachers' guide for acid rain, entitled *Exploring Acid Rain: A Curriculum Guide and Resource for Teachers of Grades 7–12* (*http://hubbardbrookfoundation.org/exploring-acid-rain-a-curriculum-guide*).

Science Links reports are modeled in part after the *Issues in Ecology* series developed by the Ecological Society of America (e.g., Vitousek et al. 1997) but expand on


Will ecosystems in the Northeast recover?

The Clean Air Act has had positive effects, but is not sufficient to fully recover acid-sensitive ecosystems in the Northeast.

SUMMARY: To date, national electric utilities have met or surpassed the emissions targets set by the 1990 CAAA. Nevertheless, data suggest that these targets will not be sufficient to achieve the full recovery of sensitive ecosystems. In order to evaluate the extent to which historic and future emissions reductions will facilitate ecosystem recovery from acid deposition, a computer model was used to estimate the relationship between emissions, deposition, and chemical recovery at the intensively studied HBEF.

DETAILS: The five chemical indicators defined in the previous sections were used in the computer model PnET-BGC to predict how future reductions in sulfur dioxide emissions may affect chemical conditions at the HBEF. The model compared current emissions reductions required by the 1990 CAAA with an additional 40 percent and 80 percent cut in *electric utility emissions* of sulfur dioxide (i.e., the equivalent of 22 and 44 percent of total sulfur dioxide emissions) by 2010. These scenarios are based on the electric utility sulfur dioxide emission reductions embodied in five bills introduced in Congress.

The computer model considered only changes in sulfur dioxide emissions. It was assumed that nitrogen oxide and ammonia would remain basically unchanged. While nitrogen is ecologically important, in the absence of a pollution cap, decreases in nitrogen oxide emissions are not expected to be large enough over the next ten years to contribute significantly to recovery. Nevertheless, nitrogen oxides play an important role in the frequency and intensity of periodic acid episodes and are an important part of emissions control strategies.

Acidification models

Scientists have developed computer models that depict the physical, chemical and biological processes within forest watersheds. Acid deposition models can be used as research and management tools to investigate factors responsible for the historical acidification of soil and water as well as the ecosystem response to anticipated future changes in acid deposition. In order to effectively predict the pH, ANC and aluminum concentrations in streams, all major chemicals must be accurately simulated (e.g., sulfate, nitrate, calcium, magnesium). The acidification model PnET-BGC was used for this assessment because it has been rigorously tested at the HBEF and other sites in the Northeast, and it allows the user of the model to consider the ecosystem response to multiple chemicals simultaneously.

PAGE 20 / *Acid Rain Revisited*

Figure 4. Excerpt from Science Links report **Acid Rain Revisited** ***shows the telescopic communication approach used to translate key findings using a question, a one-sentence answer, a summary paragraph, and more detailed descriptions. Reprinted from Driscoll et al. 2001b with permission from the Hubbard Brook Research Foundation.***

this model in at least one important way: the likelihood of specific policy options to meet established standards or thresholds for recovery are evaluated (e.g., state water-quality standards, human health criteria). Unlike a traditional journal article, Science Links reports are structured to present the conclusions first, followed by supporting information, and use a "telescopic approach," with layered details (figure 4). This approach serves the needs of decisionmakers, who may skim the report, as well as those looking for detailed supporting evidence. The reports contain compelling images and conceptual diagrams developed by professional graphic artists that depict policy-relevant findings and display quantitative information in accessible formats (figure 5). Approximately 5,000–10,000 copies are made of each Science Links report, and they are distributed through the mail, offered at display tables at conferences and events convened by other organizations, and handed out to decisionmakers at meetings and briefings arranged by HBRF. The reports are also available for download as PDF files on the HBRF Web site.

Outreach to broader audiences. Although Science Links publications are the centerpiece of the program, they are considered a means to an end, not the end itself. Additional outreach activities are undertaken to amplify the findings from these publications and to ensure their use by key policymakers. The Science Links program and other initiatives have demonstrated that personal relationships are at the center of outreach to policymakers (e.g., Uriarte et al. 2007, Pouyat et al. 2010). Science Links provides the necessary supporting mechanism for establishing and sustaining relationships by facilitating a two-way exchange with policymakers and other stakeholders (table 1).

At the outset of each of the Science Links projects described here, HBRF staff organized briefings to introduce the project to a range of stakeholders (table 1). These briefings included an overview of the issue (e.g., acid rain, nitrogen, mercury), preliminary questions to be addressed, and a qualitative description of the anticipated outcomes and their relevance to current policy issues. Through this early outreach, HBRF gathered feedback from policy stakeholders and built an informal network to consider and apply analyses. Approximately half of these briefings were held with nongovernmental organizations or trade associations, and half were held with state and federal agencies. Once preliminary results were available, a second set of briefings was organized to provide a preview of the findings and to bridge the often-extended period between manuscript submission and publication. When the publication was released and throughout the subsequent year, presentations were given to connect the results to specific policy actions, with a focus on public-sector entities that had direct oversight regarding the issues addressed in the Science Links publications, such as congressional committees, state legislature agencies, attorneys general (when they were relevant), and the Environmental Protection Agency (EPA). The briefings were tied directly to research that had been published or was soon to be published and were released to the media with reference to policy issues for which these groups have responsibility; the briefings were well attended.

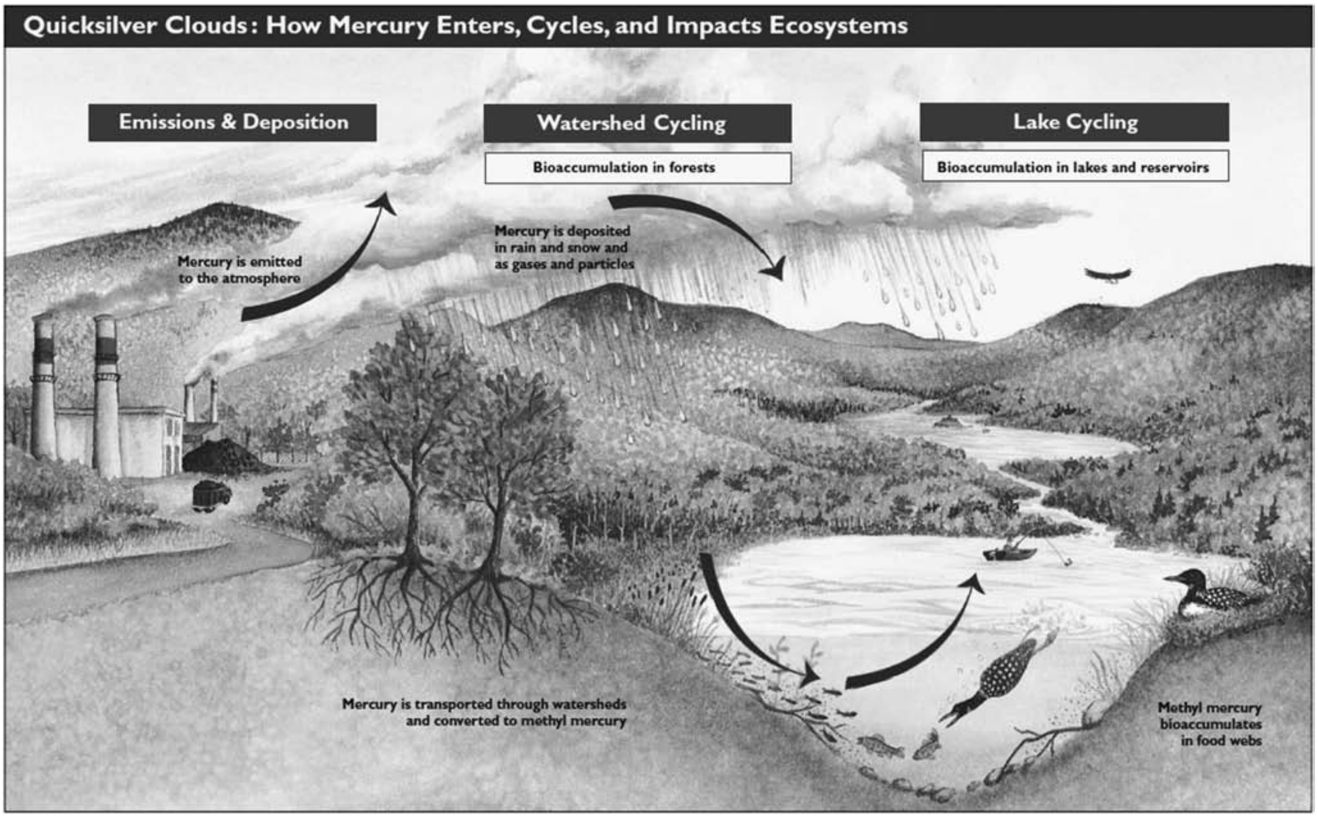


Figure 5. Science Links publications use simplified conceptual diagrams to convey complex ideas such as the diagram from Mercury Matters showing the sources and bioaccumulation of methyl mercury in fish. Reprinted from Driscoll et al. 2007b with permission from the Hubbard Brook Research Foundation.

Although the scientific basis of the three Science Links projects discussed here was mainly in the northeastern United States, the project staff purposely tackled issues of national policy significance. HBRF's outreach capacity and geographic reach was expanded through partnerships with other established science-based organizations, including the public affairs offices of the academic institutions of science team members and scientific societies (e.g., AIBS, Ecological Society of America). For instance, together with the Ecological Society of America, HBRF organized congressional briefings in Washington, DC, that featured the Science Links findings from the Acid Rain Revisited and the Nitrogen Pollution project in the Northeast, alongside related efforts from other regions of the United States. HBRF partnered with a nonpartisan, nongovernmental organization—the Society for the Protection of New Hampshire Forests—to reach natural-resource managers through a regional conference on acid rain effects on Northeast forests that offered continuing education credits to foresters. The Acid Rain Revisited project also provided a bridge between emerging research and legal actions of the ongoing New Source Review project related to the Clean Air Act by convening a workshop for project scientists and staff from the attorney general offices of the Northeast states on regional air pollution effects.

The original concept for Science Links did not include the media. Project leaders were aware of efforts to enhance scientists' interactions with the media (e.g., Aldo Leopold Leadership programs), but they expected to bypass this challenging process by engaging directly with policymakers. However, through interactions with agency officials and congressional staff, the project leaders learned that media coverage can play a critical role in verifying the public value and societal importance of an issue or set of findings. Therefore, before releasing the results of the first Science Links project, Acid Rain Revisited, HBRF worked with communication experts to develop and implement a media strategy. This strategy included releasing the major findings through a press conference, distributing supporting press releases (usually a national release and series of state-based releases with local findings), identifying policymakers who were prepared to comment on the relevance to current issues, providing advanced media training to the Science Links coauthors, and making the authors available for interviews with journalists.

Outcomes and impact of the Science Links program

Judged by a summary of project outcomes, Science Links has been a productive program: The three projects discussed here have resulted in three core and nine related peer-reviewed

Table 1. Summary of the outcomes and impact of three Science Links projects.

	Outcomes						Impact		
	Scientific publications		General publications						
Project	Number	Published in	Number	Published in	Number of briefings	Other activities	Science contribution: Number of citations	Public awareness: Earned media (not advertising or paid programming)	Policy relevance: References in major policy documents
Acid Rain Revisited	1	*BioScience*	6	HBRF factsheet, SL report, teachers' guide, book chapter, encyclopedia chapters (2)	35	Congressional testimony, regional acid rain conference, joint US Senate–House briefing organized with the ESA	303	281	New Source Review, proposed federal legislation: Clean Power Act
Nitrogen Pollution	6	*BioScience, Environment*	2	HBRF fact sheet, SL report	25	Briefing for Attorneys General in the Northeast	955	101	State NO_x SIP call, New Source Review case
Mercury Matters	3	*BioScience, Environmental Pollution*	1	HBRF SL report	41	Comments by 35 scientists on CAMR, congressional testimony, New York Times Op-Ed (Evers and Driscoll 2007)	105	>93	National Mercury Monitoring Bill, CAMR Rule (legal brief)

Note: There was a media release for each of these projects. Earned media for the acid rain and nitrogen projects were based on clips provided by LUCE clip service, whereas the mercury stories were based on a search using LexisNexis. CAMR, Clean Air Mercury Rule; ESA, Ecological Society of America; HBRF, Hubbard Brook Research Foundation; SIP, state implementation plan; SL, Science Links.

publications, more than 100 policy briefings, and nine documents for nontechnical audiences (table 1). Qualitative measures, such as attendance at briefings, requests for additional information, and solicitations for additional articles in nonscientific publications, suggest that the Science Links projects resonated with audiences ranging from landowners concerned about air pollution impacts on their forests to members of Congress and senior agency administrators directly involved in policy formulation. Consistent with HBRF's original intention, the questions addressed in the projects matched contemporary policy issues well (figure 1, box 1). In addition, the NSF LTER program identified Science Links as a model for expanding the impact of ecological research (NSF 2002).

In order to quantify the impact of the Science Links projects, we asked the following basic questions: Did each project make a valuable contribution to the literature, measured by the number of scientific citations? Did each project raise public awareness of pertinent issues through widespread and accurate media coverage, measured by the quality and quantity of that media coverage? Did each project influence related policies as would be indicated by the inclusion of Science Links results in state, regional, or national policy decisions or documents?

According to the number of citations tracked through the Web of Science's Science Citation Index, the synthesis articles are highly cited. To date, the mercury publications have received 100 citations, and the nitrogen and acid rain publications have received over 900 and 300, respectively. Media interest was high for all three projects (table 1). On the basis of results from collected press clips and a search of keywords using LexisNexis Academic, we concluded that the media coverage of each project was considerable and ranged from more than 90 media reports for the Mercury Matters project to more than 250 for the Acid Rain Revisited project. Worldwide coverage of the Acid Rain Revisited project helped revive policy attention on the continuing issue. The media coverage on the Nitrogen Pollution project was focused on the implications for emissions controls through the New Source Review provisions of the Clean Air Act, which were in dispute at the time. Media coverage of the Mercury Matters project through pieces such as the New York Times Op-Ed (Evers and Driscoll 2007) and National Public Radio's *Science Friday* helped to coin the phrase *biological mercury hotspots*, which proved influential in the policy realm by calling attention to landscape variability in sensitivity to mercury deposition, which could influence the effectiveness of a mercury emissions trading program.

The level of influence that a particular study or assessment has on public policy is difficult to assess (Clark et al. 2006). Nevertheless, we found many examples that provide supporting evidence for the influence of Science Links projects on related public policy at the state, regional, and federal levels and the extent to which leading policymakers utilized project findings (see box 1).

Analysis and lessons from the front lines

On the basis of our experience, insights from the literature, and the tangible results of Science Links, we have distilled several conceptual approaches and practical lessons that can inform future science–policy-interface initiatives. We also outline a set of challenges and provide recommendations for the advancement of such work.

Spanning the boundaries of science and policy. Literature reviews and case studies point to boundary-spanning work as perhaps the single most important factor in determining the success of science–policy integration efforts (Cash et al. 2003, McNie 2007). *Boundary spanning* refers to "practices and processes that facilitate bringing science and society closer together in order to produce and disseminate 'useful' information—that is, information that is salient, credible and legitimate" (McNie et al. 2008, p. 9). Boundary-spanning efforts can be undertaken by organizations or individuals (*boundary-spanning agents*), although there is growing evidence that their effectiveness depends in large part on their ability to establish trust and to facilitate interactions among groups that allow scientists to retain their (scientific) authority, independence, and integrity (Cash et al. 2003, McNie et al. 2008). The literature further suggests that this work is strengthened if the boundary-spanning agent is embedded within an organization that has a reputation as being an independent research organization, separate from special interests and political influence. HBRF's Science Links program has benefited from having both staff who serve as boundary-spanning agents and recognized independent scientists associated with a research-based, formalized group (i.e., the HBES).

Despite the acknowledgement in the literature of the important role that boundary-spanning organizations can play, there were obstacles to overcome in launching and implementing Science Links. For example, during the Futures Assessment project, we encountered some who felt that this work should not be undertaken and were concerned that it might compromise the integrity of the science. These concerns were addressed in part by committing to the publication of peer-reviewed synthesis articles, which helped to ensure that the project outcomes met high scientific standards.

We were also confronted with disagreement over whether our boundary-spanning efforts should reach beyond the HBES with respect to participants, data sets, and topics to be addressed (e.g., mercury). On the basis of input from the policy advisers, we resolved to develop a core team of HBES scientists and to draw extensively on long-term research and data from the HBES but to supplement that with expertise and data from across the region, so that the results would reflect conditions and understanding beyond a single site and would therefore better serve the needs and interests of policymakers.

Scaling the coproduction of knowledge. Among the most important activities of boundary-spanning work is the joint production (or *coproduction*) of knowledge. *Coproduction* refers to the process of bringing together experts and decisionmakers in a collaborative process to develop outputs (i.e., synthesis publications) that are salient and useful to the end users (after Cash et al. 2003).

As a practical matter, there is often a tension between inclusivity in the coproduction process and the need to produce timely results that adhere to the rules of scientific evidence in a manner that balances scientific opportunity and social need. Science Links balances these demands by scaling the process of coproduction to the specific objectives of the project. Since the target end users for the Science Links projects were state and federal agency personnel and lawmakers, HBRF consulted with professionals from these sectors about their information needs. For the purposes of the development and assessment of related environmental rules and regulations, it was more valuable to have a policy-relevant synthesis and associated outreach materials that represented the best available science than to have a consensus document from a diverse set of stakeholders. The Science Links team leaders decided, therefore, to pursue an approach of scaled coproduction, with four to six policy advisers, largely from the public sector, and did not formally engage interest groups, such as environmental advocacy organizations, sporting groups, or industry representatives, directly in the development of Science Links articles or reports. Information sharing with additional stakeholders was facilitated through organized briefings. If the objective had been to change individual behaviors, shape local decisions, or promote voluntary action by the regulated community, the process of coproduction would probably have been very different.

Brokering policy options. The disconnect between science and policy is sometimes viewed simply as a deficit of scientific information, which leads to the erroneous conclusion that more information will compel more-effective policy action (Lawton 2007, Groffman et al. 2010, Pouyat et al. 2010). However, scholars who study the interface between science and policy suggest that the lack of attention to the significance of science to particular policy options (Pielke 2007, Clark 2009, Pouyat et al. 2010); the inability to frame information in terms that resonate with end users (Nisbet 2009, Groffman et al. 2010); and the failure to address environmental challenges with integrated, flexible policies that promote learning and adaptation (Holling 1995) are larger obstacles. Pielke (2007) suggested that the role of the "honest broker of policy options" can facilitate more-effective science–policy linkages. *Broker of policy options* refers to people who seek "to expand, or at least clarify, the scope of choice available to the decision-maker" (Pielke 2008, p. 40). Science

Links projects support the brokering of policy options by providing a formal mechanism for producing policy-relevant synthesis publications in which the potential impacts or unintended consequences of a specific range of policy options are analyzed for issues currently under consideration by decisionmakers (e.g., varying levels of sulfur dioxide and nitrogen oxide emissions, options for decreasing nitrogen loading to estuaries through controls from different sectors, the persistence of local elevated contamination of mercury related to trading of mercury emissions). HBRF found this approach to be effective in maintaining the integrity of the science and the reputations of the scientists involved while providing salient and credible information to policymakers.

Practical lessons. After 13 years of experience with the Science Links program, we offer the following lessons learned related to project structure, synthesis efforts, and distillation and outreach:

Future projects should be structured such that teams of motivated participants are formed that are large enough to represent the disciplinary expertise and geographic reach needed for the project but small enough for effective project management (i.e., 10–12 scientists, 4 to 6 policy advisers). Projects should provide logistical and funding support for the teams and the project should be designed to provide tangible incentives (e.g., high-profile, peer-reviewed publications). Finally, they should provide adequate staffing, with experience in boundary-spanning activities, and engage supporting experts (graphic designers, communication professionals) as is needed to facilitate distillation and outreach activities.

For effective distillation, synthesis projects should be organized around a set of three or four policy-relevant questions that are defined in collaboration with the policy advisers. Future project leaders should choose an appropriate project scope: Do not make the scope too broad or extend the synthesis to areas outside the scientists' core area of expertise (e.g., law, economics, human health). Standards should be developed for data and information that include, to the extent that it is possible, the use of long-term data (defined as a record of at least 10 years), robust monitoring programs (e.g., National Atmospheric Deposition Program), or regional survey data that have been published in the peer-reviewed literature. The synthesis is strengthened and made more relevant if it is regionalized beyond one or two particular study areas to demonstrate how site-specific research and results relate to a broader area. Peer-reviewed, published models should be used to analyze the likelihood that specific policy options will meet established environmental standards or will promote recovery. Finally, project leaders should focus on the relevant science: Avoid advocating for specific legislation or policies.

Adequate resources and time need to be allocated in order to develop outreach materials that are accessible and delivered in a format that meets the needs of targeted decisionmakers. Issue advocates (Pielke 2007) should not be relied on to translate the science and to distill the implications for policy. Projects can be facilitated by partnering with other science-based organizations with similar missions to expand the impact of the project through additional briefings and other activities (e.g., conferences, Webinars). Finally, outreach to journalists and media organizations should be included as a core part of the project. This work is most effective if it is supported through a written media strategy and through training for project scientists. In our experience, there were few examples of distortion of the message or results, and we attribute this effectiveness to advance work organized by HBRF.

Challenges and recommendations. On the basis of our experience with the Science Links program and a search of the literature, we believe that an integrated approach is needed to improve the scientific basis for environmental decisionmaking. Although we believe that boundary-spanning efforts such as Science Links have key roles to play, they face several practical challenges. These include the capacity to sustain interactions with decisionmakers in support of long-term decisionmaking and assessment needs (Pouyat et al. 2010), the availability of practitioners skilled in the work of boundary-spanning functions across a range of scales (e.g., local, regional, national, global), and limited funding and incentives for the work of bridging science and policy. This scholarly work does not fit into the conventional categories of research, issue advocacy, or traditional science communications. To address these challenges, we recommend that federal funding agencies, private foundations, and others invest in boundary-spanning activities in ecosystem science, much as the National Institutes of Health and other entities have directly supported "translational research" and "bench-to-bedside" programs for the health sciences. Such programs should advance the discipline of science and policy integration in the ecosystem sciences by developing training programs in boundary-spanning functions for graduate students and later-career-stage professionals. Such training should include competency in environmental science, public policy and analysis, facilitation and group leadership, writing and distillation, stakeholder engagement, science communications, and media strategy. The programs should also expand incentives and rewards to encourage academic and government scientists to participate in policy-relevant synthesis activities. For example, greater recognition of the importance of synthesis as a scholarly endeavor by research administrators and tenure and promotion committees could help diversify and increase the pool of scientists willing to invest their time in activities that may not advance new theory but that may help address pressing societal issues (Uriarte et al. 2007). These projects should create new regional-scale, boundary-spanning programs within credible ecosystem research organizations in order to promote the development of this capacity from within the scientific community; these programs should complement existing national-scale assessment programs, such as those housed within federal agencies. They should ensure that these programs are designed as sustained efforts that provide for long-term relationship building, iterative knowledge development, and an ongoing presence in long-running policy discussions. The science of the HBES and other long-term or synthetic research efforts are particularly well suited for this work and could serve as a way to focus programmatic investment in this activity. Finally, these projects should include assessment and evaluation activities to accelerate learning in the field of science and policy integration. Although literature from the social sciences and from science and technology policy provide important insights gleaned from the study of largely national- and global-scale environmental assessments, bridging work is needed at all levels of environmental decisionmaking. Investing in assessment and evaluation activities conducted by practitioners as part of field-based projects will promote greater diffusion of innovations in this field.

Conclusions

The complexity of current environmental issues and the evolving expectations of the role of scientists and scientific institutions call for expanded approaches for the integration of the ecological sciences and environmental policy. HBRF's Science Links program provides a practical model for building that interface. First, the program provides a formal mechanism through which leading scientists work with policy stakeholders to synthesize policy-relevant research through a process of scaled coproduction. Second, the participants do not advocate a single course of action but, instead, serve as scientific brokers of policy options by analyzing the potential environmental consequences of a range of approaches. And third, communication and outreach efforts are an integral component of Science Links and are conducted throughout the course of each project.

Considering the multimillion-dollar investment required for such long-term studies, environmental observatories, specialized centers, and research networks designed to generate data and—ultimately—knowledge aimed at addressing society's "grand challenges" in environmental science, it is imperative that greater investment be made in science–policy integration and the assessment and advancement of new approaches to this important work. We recommend that private foundations, public funding agencies, scientists, and communicators work together to develop innovative boundary-spanning programs for science and policy efforts that expand the capacity for effective engagement by scientists and scientific institutions in the development of informed public policy.

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