

Who needs environmental monitoring?

Gary M Lovett^{1*}, Douglas A Burns², Charles T Driscoll³, Jennifer C Jenkins⁴, Myron J Mitchell⁵, Lindsey Rustad⁶, James B Shanley⁷, Gene E Likens¹, and Richard Haeuber⁸

Environmental monitoring is often criticized as being unscientific, too expensive, and wasteful. While some monitoring studies do suffer from these problems, there are also many highly successful long-term monitoring programs that have provided important scientific advances and crucial information for environmental policy. Here, we discuss the characteristics of effective monitoring programs, and contend that monitoring should be considered a fundamental component of environmental science and policy. We urge scientists who develop monitoring programs to plan in advance to ensure high data quality, accessibility, and cost-effectiveness, and we urge government agencies and other funding institutions to make greater commitments to increasing the amount and long-term stability of funding for environmental monitoring programs.

Front Ecol Environ 2007; 5(5): 253–260

We use monitoring data routinely in our daily lives; we monitor the stock market, the weather, our blood pressure, and baseball statistics. But, does monitoring have a place in environmental science? Common criticisms of environmental monitoring are (1) that it is not really science, but merely a fishing expedition that diverts funds from “real” science, (2) that most monitoring data are never used, and (3) that we can’t possibly know today what critical questions will need to be answered in the future. Some people feel that monitoring has no place in rigorous environmental science, and mindless monitoring gives the discipline a bad reputation. Who needs it?

In a nutshell:

- Environmental monitoring is often criticized as being unscientific, expensive, and wasteful
- We argue that monitoring is a crucial part of environmental science, costs very little relative to the value of the resources it protects and the policy it informs, and has added value in that basic environmental monitoring data can be used for multiple purposes
- Effective monitoring programs address clear questions, use consistent and accepted methods to produce high-quality data, include provisions for management and accessibility of samples and data, and integrate monitoring into research programs that foster continual examination and use of the data
- Government agencies should commit to long-term support for valuable monitoring programs, and funders of basic ecological and environmental research should recognize that monitoring is a fundamental part of environmental science

In this paper, we evaluate these common perceptions of environmental monitoring and discuss the characteristics of successful and unsuccessful monitoring programs. We define environmental monitoring as a time series of measurements of physical, chemical, and/or biological variables, designed to answer questions about environmental change. These measurements may be taken at one or multiple locations. The meaning of “long term” depends on the time scale of the ecological process of interest, but in this paper we focus on datasets that span decades. Our discussion is particularly relevant, given the budgetary constraints on current monitoring and the ongoing debate regarding the opportunities, limitations, and costs associated with the establishment of national environmental observatories in the US, for example the National Ecological Observatory Network (NAS 2004), the Hydrologic Observatories, and the Cooperative Large-scale Engineering Analysis Network for Environmental Research (NRC 2006).

■ Is monitoring science?

Good science involves more than just devising clever experiments to test a specific hypothesis. Carpenter (1998) suggests that ecosystem science is like a table supported by the four legs of theory, experimentation, cross-site comparisons, and long-term studies. Many ecosystems require long-term study because they change slowly, and sustained monitoring of key variables provides the principal record of change. Long-term monitoring data also provide context for short-term experiments and observations. For example, suppose an elegant irrigation experiment is conducted to determine the effect of water availability on plant production, and no response is observed. If long-term measurements of precipitation indicate that the experiment occurred during the wettest year on record, the monitoring data provide important information for interpreting these unexpected experi-

¹Institute of Ecosystem Studies, Millbrook, NY *(lovettg@ecostudies.org); ²US Geological Survey, Troy, NY; ³Syracuse University, Syracuse, NY; ⁴University of Vermont, Burlington, VT; ⁵College of Environmental Science and Forestry, State University of New York, Syracuse, NY; ⁶US Department of Agriculture Forest Service, Cumberland, ME; ⁷US Geological Survey, Montpelier, VT; ⁸US Environmental Protection Agency, Washington, DC



Courtesy of EPA Clean Air Markets Division

Figure 1. The National Atmospheric Deposition Program (NADP) and Clean Air Status and Trends Network (CASTNET) site at Prince Edward, VA. These two atmospheric monitoring networks are crucial for quantifying atmospheric deposition and tracking responses to air-pollution legislation. The two tall towers and the instrument shed at the left of the photo hold the instrumentation for the air chemistry and dry deposition measurements made by CASTNET, and the automatic precipitation collector at the right of the photo is used by the NADP for measuring precipitation chemistry.

mental results. Monitoring data are also necessary for determining whether an event is unusual or extreme and are useful for the development of appropriate experimental designs. For example, long-term monitoring of atmospheric ozone provides the critical information on average and extreme ozone concentrations that is needed to design an appropriate experiment examining the effects of ozone on plants. Monitoring data also contribute significantly to the parameterization and testing of environmental models, such as the general circulation models (GCMs) that predict future climate change. Clearly, monitoring is a crucial part of environmental science.

Proposals that include monitoring generally do not fare well in competition for basic science funding from competitive grant agencies, such as the US National Science Foundation. Reviewers often object on the grounds that monitoring does not address a hypothesis, or that the hypothesis is trivial. However, careful, structured observation is as fundamental to science as is hypothesis testing. Good, long-term monitoring records are rare and extremely valuable.

Haphazard monitoring, of course, adds little to scientific knowledge. However, this also applies to other forms of scientific endeavor; when theory, experiments, or cross-site comparisons are poorly designed or imple-

mented, they also add little to scientific understanding. The keys to good science are similar for all forms of scientific inquiry, including monitoring: good questions, appropriate research designs, high-quality data, and careful interpretation of the results.

■ Is monitoring cost-effective?

Monitoring not only provides the basis for formulation of science-based environmental policy, but continued monitoring also permits evaluation of whether the policy has had its intended effect and has been cost-effective. Solutions to many environmental problems are expensive and technically challenging, but the cost of monitoring programs is generally much less than either the cost of policy implementation or the monetary benefits associated with environmental improvement. The cost-effectiveness of monitoring in implementing environmental policy is illustrated below by three examples of major environmental issues and their related monitoring efforts.

Clean Water Act

The Clean Water Act (CWA) of 1972, along with subsequent amendments, has established the modern framework for regulating water pollution in the rivers, lakes, wetlands, and coastal waters of the US. The CWA regulates discharge from municipal wastewater treatment plants and industrial facilities, non-point source pollution from agricultural activities, wetlands protection, and many other activities. The cost of water-quality monitoring under the CWA is difficult to estimate because of the diffuse responsibilities of federal, state, and local agencies under various sections of this complex law. Accordingly, estimates of the total costs of complying with the CWA vary widely, from \$14.1 billion per year (in 1997 dollars; Van Houtven *et al.* 2000) to as high as \$93.1 billion per year (in 2001 dollars; Johnson 2004). Judging the effectiveness of these expenditures in improving water quality has been contentious (Smith *et al.* 1987; Knopman and Smith 1993), due in part to concerns about the quality, statistical representativeness, and comparability across states of long-term water quality measurements, which are largely the responsibility of individual states (Adler *et al.* 1993; GAO 2000; Hirsch *et al.* 2006). A recent estimate of government expenses for regulation and monitoring under the CWA puts the cost at \$982 million in 2001, of which much less than half is likely to be attributable to water-pollution monitoring (Johnson 2004). If as much as one-third (probably an overestimate) of these expenses are for actual water-quality monitoring, then this value represents only 0.4–2.1% of the estimated cost of complying with the CWA.

Acid deposition

Acid deposition has been an important scientific and policy issue in North America since the 1970s. Major policy action was taken in the 1990 amendments to the Clean Air Act, in which Title IV is focused on protecting ecosystems from acidifying deposition of sulfur and nitrogen. Title IV has resulted in major reductions in emissions of sulfur dioxide (SO₂) and nitrogen oxides (NO_x) by electric power generation plants. By 2005, Title IV emission reduction programs had diminished annual SO₂ emissions by more than seven million tons from 1980 levels, and had reduced annual NO_x emissions by over three million tons from 1990 levels. The most recent analysis of the benefits and costs of compliance with Title IV estimated the program's benefits at \$122 billion annually in 2010, when the program will be fully implemented, while projecting the annual cost to industry of compliance at approximately \$3 billion (in 2000 dollars; Chestnut and Mills 2005).

Changes in acid deposition resulting from Title IV are primarily monitored by two networks (Figure 1): the National Atmospheric Deposition Program (NADP), which measures precipitation chemistry in the US at a cost of approximately \$6 million annually (V Bowersox pers comm), and by the Clean Air Status and Trends Network (CASTNET), which measures ozone and dry deposition at a cost of approximately \$3.9 million annually. In addition to these air-quality monitoring programs, the US Environmental Protection Agency (EPA) has two surface-water monitoring programs to assess the response of acid-sensitive watersheds to changes in atmospheric deposition (Stoddard *et al.* 2003); they are the Temporally Integrated Monitoring of Ecosystems (TIME) and the Long-Term Monitoring (LTM) program, which differ in intensity of sampling and selection of sampled lakes and streams. The TIME/LTM program currently focuses on the areas most impacted by acid deposition: lakes in the Adirondack Mountain region of New York and New England and streams in the Northern Appalachian Plateau and Blue Ridge region of Virginia and West Virginia. The scope and budget of this program has been markedly reduced, from \$2 million annually in the early 1990s to substantially less than \$1 million today. Taken together, the total cost of these critical atmospheric deposition and surface-water monitoring programs represents less than 0.4% of the implementation costs of Title IV and less than 0.01% of the estimated benefits.

Carbon sequestration

The potential for vegetation in the US to sequester carbon is important for the analysis of global carbon budgets



Figure 2. US Department of Agriculture Forest Service technicians measure decaying wood in the Delaware River Basin as part of the Forest Inventory and Analysis (FIA) program. The FIA program monitors forest health and productivity throughout the US (www.fia.fs.fed.us/).

and, in addition, may be of future economic importance if the US adopts a carbon-trading program that includes credits for carbon sequestration. The potential for US forests to sequester atmospheric CO₂ has been estimated from the data collected by the US Department of Agriculture Forest Service's Forest Inventory and Analysis (FIA) program (Birdsey 1992; Birdsey and Lewis 2003; Figure 2). The primary goal of the FIA program is to monitor the extent, condition, productivity, uses, impacts of management, and health of forest ecosystems in the US, but the FIA data are used by many researchers for a wide variety of purposes, including estimation of forest carbon sequestration. Using FIA data and other information, Goodale *et al.* (2002) estimated that the annual accumulation of carbon in forest ecosystems in the US from 1990–1991 was 0.28 Pg, or 280 million tons. The monetary value of this ecosystem service is difficult to quantify. However, recent analyses of energy policy options suggest that if a carbon-trading program were implemented in the US, carbon credits could be priced at \$5 to \$25 per ton (National Commission on Energy Policy 2004, 2005), yielding a value for forest carbon sequestration of between \$1.4 billion and \$7 billion per year. The federal appropriation for FIA in 2003 was \$59.7 million, supplemented by \$10.2 million from other partners (USDA Forest Service 2004). Thus, depending on the price chosen for carbon credits, the cost of implementing the FIA program ranges from < 1% to 5% of the potential value of annual carbon sequestration in forest ecosystems in the US. This analysis is for carbon sequestration alone, and does not consider the many other important uses of FIA data, such as evaluation of forest health and timber stocks.

The above examples show clearly that while large-scale

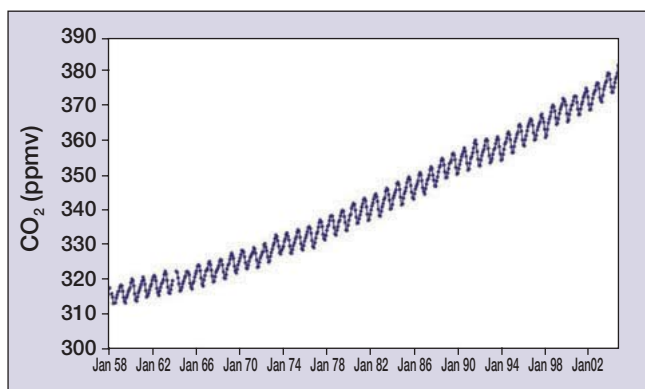


Figure 3. Mean monthly atmospheric concentrations of CO₂ measured at Mauna Loa, HI, by CD Keeling and colleagues from 1958 to 2004. Plotted from data available at the Carbon Dioxide Information Analysis Center (www.cdiac.ornl.gov).

monitoring programs often require considerable expenditures, in many cases these costs are miniscule compared to the value of the resources monitored and the policies that affect these resources. Furthermore, the absence of monitoring can greatly hinder evaluation of the effectiveness of environmental policies and programs. One example is the lack of a uniform and integrated surface-water monitoring program to assess the Clean Water Act, as discussed above. Another is the inability to assess the effectiveness of the \$14–15 billion spent on river restoration projects in the US since 1990, because these projects rarely include river monitoring before and after the restoration effort (Bernhardt *et al.* 2005). While it may seem that monitoring costs take funds away from restora-

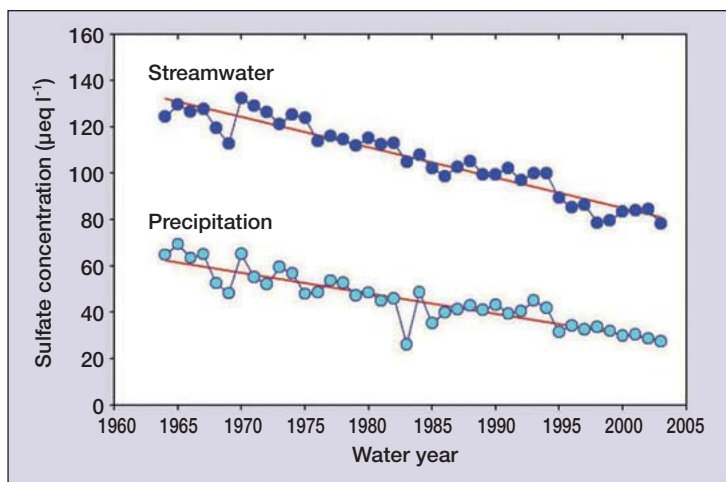


Figure 4. Long-term record of annual volume-weighted mean sulfate concentrations in bulk precipitation and streamwater in Watershed 6 of the Hubbard Brook Experimental Forest, NH (updated from Likens *et al.* 2002). This data record was initiated as part of a basic study of forest ecosystem function, but has also proven valuable in assessments of ecosystem response to policies controlling emissions of air pollutants. Monitoring at the Hubbard Brook Experimental Forest relies on an effective collaboration between academic scientists and the US Department of Agriculture Forest Service, which monitors hydrological and meteorological variables at this site.

tion work, the small fraction spent on monitoring actually provides an opportunity to learn which restoration methods work and which do not.

■ Are monitoring data used effectively?

We all know of monitoring data that have accumulated in file cabinets (or on hard drives) and gathered dust. These data may be either inaccessible to all but a few, too poor in quality or too poorly documented to be useful, or they may have been collected solely to fulfill a legal requirement, with no real motivation for thorough analysis and interpretation. At the other end of the spectrum are datasets from both individual investigators and large institutional programs that have enormous value to environmental science and policy. Consider, for example, Charles David Keeling's record of atmospheric CO₂ concentrations at Mauna Loa, Hawaii. Although Tyndall and Arrhenius proposed in the late 19th century that changes in atmospheric CO₂ concentrations could affect the heat budget and surface temperature of Earth, the concept of global climate change and its linkage with anthropogenic emissions of CO₂ did not emerge until Keeling began long-term measurements of atmospheric CO₂ at Mauna Loa in the 1950s (Figure 3). Now, global climate change is arguably the foremost issue in environmental science and policy.

Consider also measurement of the chemistry of bulk precipitation and streamwater at the Hubbard Brook Experimental Forest in New Hampshire (Figures 4 and 5). Begun in 1963, this is the longest-running precipitation and streamwater chemistry record in the US and has figured prominently in the development of the watershed–ecosystem concept, analysis of watershed biogeochemical cycles, and evaluation of forest harvesting policy (Bormann and Likens 1967; Likens *et al.* 1978; Likens and Bormann 1995). During the scientific debate that preceded the Clean Air Act Amendments of 1990, the sulfate trends (Figure 4) at Hubbard Brook were very influential in convincing scientists and policy makers that decreasing sulfur emissions would produce substantial decreases in sulfur deposition and streamwater sulfate concentrations in the northeastern US (NRC 1983).

A good example of a valuable, broad-scale monitoring program is the NADP precipitation chemistry network discussed above. The NADP data are widely used because of their high quality and free availability on the Internet. These data have proven effective in evaluating emissions policies for sulfur and nitrogen oxides. For example, they were used to measure the decline in atmospheric nitrate and sulfate deposition following the implementation of the 1990 Clean Air Act Amendments (Lynch *et al.* 2000; Butler *et al.* 2001, 2005). The NADP program also provides a powerful example of the value of the Internet in provid-

ing broad-scale access to data. Prior to 1995, when the NADP data were first made available online, fewer than 500 people per year received data on tape or diskette (V Bowersox pers comm); in contrast, more than 18 000 downloads of NADP data from the Internet have been recorded annually in recent years (NADP 2003).

Another crucial, large-scale monitoring program is the USGS national network of stream gauges, which provides fundamental data nation-wide for flood prediction and estimation of water supply. The data are used for other scientific purposes as well, including analysis of the impacts of climate change (Lins and Slack 1999; McCabe and Wolock 2002; Hodgkins *et al.* 2003) and testing the accuracy of models that predict future climate change (Milly *et al.* 2005).

The examples above are well known, but even relatively obscure datasets can be valuable if they are accessible and of high quality, and if the record is of sufficient length. Climate researchers have unearthed many long-term records that provide information on climate change. Examples from the US include the record of dates of spring-time wildflower blooming and bird arrivals that Aldo Leopold began at his Wisconsin farm in 1936 (Bradley *et al.* 1999), the changing bloom dates of lilac planted at hundreds of sites in the mid-1960s (Schwartz and Reiter 2000; Wolfe *et al.* 2005; Figure 6), and the long-term records of lake ice-out dates (Likens 2000; Magnuson *et al.* 2000; Hodgkins *et al.* 2002) and ice thickness of rivers (Huntington *et al.* 2003).

The criticism that monitoring data are collected and never used is unfortunately true in some cases, but other monitoring datasets have proven extremely important. Below, we offer some guidelines for maximizing the use and value of monitoring programs.

■ Can today's monitoring programs answer tomorrow's questions?

Good monitoring programs are designed around good questions, but will the questions asked today still be important decades into the future? Unfortunately, no one knows for certain which environmental issues will emerge and which will recede as time passes. No doubt, some scientist of the next century, desperately in need of historical data to address an important problem, will look back and wonder how environmental scientists could have failed to take some crucial measurement, whatever it might be. However, a combination of good foresight and understanding of the system being monitored can produce mon-



Figure 5. The V-notch weir at Watershed 6 of the Hubbard Brook Experimental Forest, NH. The long-term stream chemistry monitoring data shown in Figure 4 are from this stream.

itoring data with enduring value. Good foresight involves looking ahead to anticipate potentially important environmental problems of the future and selecting key measurements that are likely to be sensitive to change. Understanding the system depends on choosing the most relevant measurements among a host of possibilities in complex systems. Some variables are important because they represent critical processes (eg net primary production, nutrient budgets); others are useful because they are known controllers of ecosystem function (eg precipitation amount, phosphorus concentration in lakes); still others are important because people care about them (eg bird species diversity). Monitoring such key variables improves the probability that a dataset will be useful for the study of future environmental issues.



Figure 6. The lilac variety *Syringa chinensis*, "red rothomagensis", in full bloom. Flowering dates of clones of this plant are used for monitoring phenological trends associated with climate change throughout the US.

Panel 1. The seven habits of highly effective monitoring programs*

(1) Design the program around clear and compelling scientific questions. Questions are crucial because they determine the variables measured, spatial extent of sampling, intensity and duration of the measurements, and, ultimately, the usefulness of the data.

(2) Include review, feedback, and adaptation in the design. The guiding questions may change over time, and the measurements should be designed to accommodate such changes. The program leaders should continually ask, “Are our questions still relevant and are the data still providing an answer?” The program should have the capacity to adapt to changing questions and incorporate changing technology without losing the continuity of its core measurements.

(3) Choose measurements carefully and with the future in mind. Not every variable can be monitored, and the core measurements selected should be important as either basic measures of system function, indicators of change, or variables of particular human interest. If the question involves monitoring change in a statistical population, measurements should be carefully chosen to provide a statistically representative sample of that population. Measurements should be as inexpensive as possible because the cost of the program may determine its long-term sustainability.

(4) Maintain quality and consistency of the data. The best way to ensure that data will *not* be used is to compromise quality or to change measurement methods or collection sites repeatedly. The confidence of future users of the data will depend entirely on the quality assurance program implemented at the outset. Sample collections and measurements should be rigorous, repeatable, well documented, and employ accepted methods. Methods should be changed only with great caution, and any changes should be recorded and accompanied by an extended period in which both the new and the old methods are used in parallel, to establish comparability.

(5) Plan for long-term data accessibility and sample archiving. Metadata should provide all the relevant details of collection, analysis, and data reduction. Raw data should be stored in an accessible form to allow new summaries or analyses if necessary. Raw data, metadata, and descriptions of procedures should be stored in multiple locations. Data collected with public funding should be made available promptly to the public. Policies of confidentiality, data ownership, and data hold-back times should be established at the outset. Archiving of soils, sediments, plant and animal material, and water and air samples provides an invaluable opportunity for re-analysis of these samples in the future.

(6) Continually examine, interpret, and present the monitoring data. The best way to catch errors or notice trends is for scientists and other concerned individuals to use the data rigorously and often. Adequate resources should be committed to managing data and evaluating, interpreting, and publishing results. These are crucial components of successful monitoring programs, but planning for them often receives low priority compared to actual data collection.

(7) Include monitoring within an integrated research program. An integrated program may include modeling, experimentation, and cross-site comparisons. This multi-faceted approach is the best way to ensure that the data are useful and, indeed, are used.

*With apologies to Covey (1989)

Observation of trends or spatial patterns in monitoring data often allows us to discover emerging environmental problems and to advance environmental science in new directions. Examples include Keeling's measurements of increasing atmospheric CO₂ (Keeling *et al.* 1976; Figure 3) and the discovery of the “ozone hole” above Antarctica by a team of British scientists (Farman *et al.* 1985). Each of these discoveries led to new research and policy efforts that have reverberated around the globe.

Finally, scientists of the future will look back with profound gratitude if we archive samples and not just data. Chemical measurement techniques are sure to improve, and new problems will require analyses that have not yet been developed. When samples of soil, plant material, animal specimens, water, and other environmental media are archived, the scientists of the next century will have a treasure trove of stored information with which to answer the burning questions of the day.

■ What makes a monitoring program successful?

In this paper, we have highlighted examples of environmental monitoring that have proven useful in furthering science and policy. Yet, as we point out above, some monitoring datasets go largely unused. How can we ensure that monitoring programs, which consume our time and

financial resources, will be useful in the future?

There is no single best model for the structure of a monitoring study. Effective monitoring has been done by individuals and small groups of scientists and by large agencies, and has occurred at individual sites, across large regions, and even over entire continents. Like other forms of long-term research, the most important requirement is a personal or institutional commitment to sustain the program (Strayer *et al.* 1986). When the goal is to maintain a consistent measurement regimen for decades, there will undoubtedly be times when funding will be lean and much effort will be required to continue the endeavor. A successful program must be designed to survive lean times by maintaining a solid funding base, a core set of inexpensive measurements, and a group of individuals dedicated to collecting, interpreting, and using the data. Beyond this personal or institutional commitment, successful monitoring programs have several important characteristics of design and implementation, which we summarize in Panel 1.

■ Conclusions and recommendations

Who needs environmental monitoring? We all do. Scientists need monitoring as part of integrated environmental research programs. Policy makers need monitor-

ing to design, implement, and evaluate effective environmental policies. The public needs monitoring to track our nation's natural resources. Monitoring is not second-rate science. Rather, it is an essential component of environmental science and deserves the careful attention of scientists and greater support from government agencies and other funding sources.

If you are a scientist managing a monitoring program, your responsibility is to ensure that the data are of high quality, that data and methods are broadly accessible, and that the program is as cost-effective as possible. The "seven habits" listed in Panel 1 provide good operating principles for these programs. Greater commitment is needed to examine, interpret, and apply data that are being collected and to cooperate with other scientists in forming monitoring networks that are designed to promote comparability of data across sites and across scales of space and time.

If you are a policy maker, resource manager, or a program manager in a government agency or funding institution, your responsibility is to make the commitment to maintain and expand long-term monitoring programs. Fickleness of funding has led to the demise of many good monitoring programs, and Herculean efforts are often required by scientists to continue collecting data in the face of reduction or loss of funds. Agencies such as the US Geological Survey, the US Department of Agriculture Forest Service, the National Oceanic and Atmospheric Administration, and the US Environmental Protection Agency should evaluate their monitoring programs in the light of national needs and take steps to ensure that those programs are not sacrificed in tight budget years. The National Science Foundation and other agencies with competitive grant programs need to recognize that long-term monitoring is a critical part of the infrastructure of environmental science and that many valuable monitoring programs are funded through investigator-initiated research proposals. Maintenance of long-term monitoring datasets should be a highly valued feature in the review of proposals. At a national scale, better integration of monitoring efforts is needed to make more efficient use of the funds now being spent on monitoring by many federal and state agencies, universities, and private companies (CENR 1997), and more funding is required to monitor critical environmental indices that are not currently being measured (Heinz Center 2006).

A renewed commitment to funding environmental monitoring, and a clear focus on doing it well, will provide an invaluable legacy for future scientists and citizens.

■ Acknowledgements

This paper is a project of the Northeastern Ecosystem Research Cooperative. We thank R Skeffington for inspiration and D Sleeper for advice and encouragement on this paper. We acknowledge the support of the US National Science Foundation through its "Research

Coordination Networks" program (grant DEB-0342198) and through grants DEB 0129138 and DEB 0423259. This paper has not been subjected to EPA peer and administrative review; therefore, the conclusions and opinions contained here are solely of the authors, and should not be construed to reflect the views of the EPA.

■ References

- Adler RW, Landman JC, and Cameron DM. 1993. The Clean Water Act 20 years later. Washington, DC: Island Press.
- Bernhardt ES, Palmer MA, Allan JD, *et al.* 2005. Synthesizing US river restoration efforts. *Science* **308**: 636–37.
- Birdsey RA. 1992. Carbon storage and accumulation in United States forest ecosystems. Washington, DC: USDA Forest Service. General Technical Report WO-59.
- Birdsey R and Lewis G. 2003. Carbon in US forests and wood products, 1987–1997: state-by-state estimates. Newtown Square, PA: USDA Forest Service, Northeastern Research Station. General Technical Report NE-310.
- Bormann FH and GE Likens. 1967. Nutrient cycling. *Science* **155**: 424–29.
- Bradley NL, Leopold AC, Ross J, and Huffaker W. 1999. Phenological changes reflect climate change in Wisconsin. *P Natl Acad Sci USA* **96**: 9701–04.
- Butler TJ, Likens GE, and Stunder BJB. 2001. Regional-scale impacts of Phase I of the Clean Air Act Amendments in the USA: the relation between emissions and concentrations, both wet and dry. *Atmos Environ* **35**: 1015–28.
- Butler TJ, Likens GE, Vermeylen FM, and Stunder BJB. 2005. The impact of changing nitrogen oxide emissions on wet and dry nitrogen deposition in the northeastern USA. *Atmos Environ* **39**: 4851–62.
- Carpenter SR. 1998. The need for large-scale experiments to assess and predict the response of ecosystems to perturbation. In: Pace ML and Groffman PM (Eds). *Successes, limitations and frontiers in ecosystem science*. New York, NY: Springer.
- CENR (Committee on Environment and Natural Resources). 1997. Integrating the nation's environmental monitoring and research networks and programs: a proposed framework. Washington, DC: The White House National Science and Technology Council, Committee on Environment and Natural Resources.
- Chestnut LG and Mills DM. 2005. A fresh look at the benefits and cost of the US acid rain program. *J Environ Manage* **77**: 252–66.
- Covey SR. 1989. *The 7 habits of highly effective people: powerful lessons for personal change*. New York, NY: Free Press.
- Farman JC, Gardiner BG, and Shanklin JD. 1985. Large losses of total ozone in Antarctica reveal seasonal ClO_x/NO_x interaction. *Nature* **315**: 207–10.
- GAO (General Accounting Office). 2000. Water quality: key EPA and state decisions limited by inconsistent and incomplete data. Washington, DC: United States General Accounting Office. GAO/RCED-00-54.
- Goodale CL, Apps MJ, Birdsey RA, *et al.* 2002. Forest carbon sinks in the northern hemisphere. *Ecol Appl* **12**: 891–99.
- Heinz Center. 2006. Filling the gaps: priority data needs and key management challenges for national reporting on ecosystem condition. Washington, DC: The H John Heinz III Center for Science, Economics, and the Environment.
- Hirsch RM, Hamilton PA, and Miller TL. 2006. US Geological Survey perspective on water-quality monitoring and assessment. *J Environ Monitor* **8**: 512–18.
- Hodgkins GA, Dudley RW, and Huntington TG. 2003. Changes in the timing of high river flows in New England over the 20th Century. *J Hydrol* **278**: 244–52.
- Hodgkins GA, James IC, and Huntington TG. 2002. Historical changes in lake ice-out dates as indicators of climate change in

- New England, 1850–2000. *Int J Climatol* **22**: 1819–27.
- Huntington TG, Hodgkins GA, and Dudley RW. 2003. Historical trend in river ice thickness and coherence in hydroclimatological trends in Maine. *Climatic Change* **61**: 217–36.
- Johnson JM. 2004. The cost of regulations implementing the Clean Water Act: a working paper in regulatory studies. Fairfax, VA: Mercatus Center, George Mason University. www.mercatus.org/publications/pubid.1476/pub_detail.asp. Viewed 1 May 2007.
- Keeling CD, Bacastow RB, Bainbridge AE, *et al.* 1976. Atmospheric carbon dioxide variations at Mauna-Loa observatory, Hawaii. *Tellus* **28**: 538–51.
- Knopman DS and Smith RA. 1993. Twenty years of the Clean Water Act: has US water quality improved? *Environment* **35**: 17–41.
- Likens GE. 2000. A long-term record of ice cover for Mirror Lake, New Hampshire: effects of global warming? *Verh Internat Verein Limnol* **27**: 2765–69.
- Likens GE, Bormann FH, Pierce RS, and Reiners WA. 1978. Recovery of a deforested ecosystem. *Science* **199**: 492–96.
- Likens GE and Bormann FH. 1995. Biogeochemistry of a forested ecosystem, 2nd edn. New York, NY: Springer-Verlag.
- Likens GE, Driscoll CT, Buso DC, *et al.* 2002. The biogeochemistry of sulfur at Hubbard Brook. *Biogeochemistry* **60**: 235–316.
- Lins HF and Slack JR. 1999. Streamflow trends in the United States. *Geophys Res Lett* **26**: 227–30.
- Lynch JA, Bowersox VC, and Grimm JW. 2000. Changes in sulfate deposition in eastern USA following implementation of Phase I of Title IV of the Clean Air Act Amendments of 1990. *Atmos Environ* **34**: 1665–80.
- Magnuson JJ, Robertson DM, Benson BJ, *et al.* 2000. Historical trends in lake and river ice cover in the Northern Hemisphere. *Science* **289**: 1743–46.
- McCabe GJ and Wolock DM. 2002. A step increase in streamflow in the conterminous United States. *Geophys Res Lett* **29** doi:10.1029/2002GL015999.
- Milly PCD, Dunne KA, and Vecchia AV. 2005. Global pattern of trends in streamflow and water availability in a changing climate. *Nature* **438**: 347–50.
- NAS (National Academy of Sciences). 2004. NEON – addressing the nation's environmental challenges. Washington, DC: National Academy Press.
- National Commission on Energy Policy. 2004. Ending the energy stalemate: a bipartisan strategy to meet America's energy challenges. Washington, DC: National Commission on Energy Policy.
- National Commission on Energy Policy. 2005. NCEP staff background paper – pricing carbon: an overview. Washington, DC: National Commission on Energy Policy.
- NRC (National Research Council). 1983. Acid deposition: atmospheric processes in eastern North America. Washington, DC: National Academy Press.
- NRC (National Research Council). 2006. CLEANER and NSF's environmental observatories. Washington, DC: The National Academies Press.
- Schwartz MD and Reiter BE. 2000. Changes in North American spring. *Int J Climatol* **20**: 929–32.
- Smith RA, Alexander RB, and Wolman MG. 1987. Water quality trends in the nation's rivers. *Science* **235**: 1607–15.
- Stoddard A, Harcum JB, Simpson JT, *et al.* 2002. Municipal wastewater treatment: evaluating improvements in national water quality. Hoboken, NJ: John Wiley & Sons.
- Stoddard JL, Kahl JS, Deviney FA, *et al.* 2003. Response of surface water chemistry to the Clean Air Act Amendments of 1990. Corvallis, OR: US Environmental Protection Agency. Report EPA/620/R-03/001.
- Strayer D, Glitzenstein JS, Jones CG, *et al.* 1986. Long-term ecological studies: an illustrated account of their design, operation, and importance to ecology. Millbrook, New York: Institute of Ecosystem Studies. *Occasional Publication of the Institute of Ecosystem Studies* **2**.
- USDA Forest Service. 2004. Forest inventory and analysis fiscal year 2003 business report. Washington, DC: USDA Forest Service Washington Office. Business Report FS-806.
- Van Houtven GL, Brunnermeier SB, and Buckley MC. 2000. A retrospective assessment of the costs of the Clean Water Act: 1972 to 1997. Final report to US Environmental Protection Agency. www.epa.gov/ost/economics/costs.pdf. Viewed 23 Apr 2007.
- Wolfe DW, Schwartz MD, and Lakso AN. 2005. Climate change and shifts in spring phenology of three horticultural woody perennials in northeastern USA. *Int J Biometeorol* **49**: 303–09.