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Environmental Challenges for the Twenty-First Century: Interacting Challenges and Integrative Solutions

*Pamela Matsón**

The environmental challenges of the twenty-first century will arise from the interaction of many different human activities. The coalescence and interaction of multiple environmental problems in specific locations call for new research and management approaches. For water resources and atmospheric quality issues, management strategies that account for the influences of multiple human activities in interaction with the dynamic natural system are being developed and evaluated. What is still needed are strategies that deal not just with water or air resource issues separately, but with multiple resource issues as they interact with each other in specific places at specific times.

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INTRODUCTION

The Bruntland Commission, in their landmark 1987 document, *Our Common Future*,¹ evaluated the challenges associated with development in industry, urban systems, agriculture, energy, and human population growth.² In the 1999 book entitled *Our Common Journey: A Transition Toward Sustainability*, the National Research Council revisited these sectors to discuss progress made over the past decade, remaining challenges, and opportunities for accelerating environmentally-sustainable progress.³ Perhaps surprisingly, the authors concluded that, while each sector faces substantial challenges and environmental threats associated with development, none of those threats alone is likely to derail a transition to sustainability.⁴ Rather, it is the combination and intersection of problems and resource demands across all the sectors that have the potential to prevent the transition.

In past decades, our environmental concerns have focused on urban air pollution, toxic chemicals, acid rain, climate change, and many other problems that plague specific locations. Our research, management, and policy enterprises have dealt with each environmental concern more or less independently; today and in future decades, we must focus on the interactions among them. No longer can we ask about the consequences of, for example, climate change on agricultural ecosystems; instead, we must ask about the combined effects of climate change, elevated carbon dioxide, soil quality changes, crop management changes, and tropospheric and stratospheric ozone changes on crop productivity. Likewise, it makes little sense to ask about climate change effects on coral reefs when concomitant changes in land use and urban, industrial, and agricultural effluents act in concert with global changes, such as increased concentrations of carbon dioxide and increasing temperature, to alter these systems.⁵ In the next decade, we will see research and problem solving shift from focusing on single issues to concentrating on

1. WORLD COMM'N ON ENV'T AND DEV., *OUR COMMON FUTURE* (1987).

2. *See id.*

3. BD. ON SUSTAINABLE DEV., NAT'L RESEARCH COUNCIL, *OUR COMMON JOURNEY: A TRANSITION TOWARD SUSTAINABILITY* (1999) [hereinafter, *OUR COMMON JOURNEY*].

4. Matson was a member of the Board on Sustainable Development and a co-author of *Our Common Journey*, and bases some of her remarks herein on the thinking and writing of that group.

5. *See P. M. Vitousek et al., Human Domination of Earth's Ecosystems*, 277 *SCI.* 494 (1997).

the effects of multiple interacting stresses.⁶ Moreover, we must begin to examine the interactions of local and global changes in the context of particular places and populations (that is, in a "place-based" research and decisionmaking context).

In the following paragraphs, I discuss some of the integrative, interactive challenges that confront us as we struggle to meet the needs of a growing and developing human population. I suggest areas where we need new scientific knowledge and management approaches to address them. I start with examples of integrative approaches for dealing with single resource issues having to do with water and air. Then, I discuss the need for strategies that deal with multiple and interacting environmental changes. Finally, I suggest that integrative, place-based analysis is key to managing for development, resource conservation, and environmental protection.

I

WATER

Almost all human activities depend on the availability of clean water. At the same time, these human activities greatly influence the availability of clean water. Water links industry, energy, human health, urban development, agriculture, and the diversity and functioning of biological systems. At the global level, the supply of fresh water has been dramatically altered by human activities—Postel *et al.* estimate that 54% of accessible global run-off is being used by humans.⁷ Even so, global numbers suggest adequate per capita water worldwide. But these numbers are deceiving—variable distributions of fresh water lead to great disparities in access to water, with scarcities in some areas and excesses in others. Thus, in a number of regions, due to insufficient amounts in some places and to poor water quality in many others, water is in short supply relative to current needs. As regional populations grow and urban systems develop, these stresses are accelerating due to conflicting and increasing demands for water supply.⁸ In many parts of the world, conflicts over water rights cause continuing social and

6. See COMM. ON GLOBAL CHANGE RESEARCH, NAT'L RESEARCH COUNCIL, GLOBAL ENVIRONMENTAL CHANGE: RESEARCH PATHWAYS FOR THE NEXT DECADE (1998); OUR COMMON JOURNEY, *supra* note 3.

7. S. L. Postel, G. C. Daily & P. R. Ehrlich, *Human Appropriation of Renewable Freshwater*, 271 *SCI.* 785, 788 (1996).

8. See Peter H. Gleick, *Effects of Climate Change on Shared Fresh Water Resources*, in *CONFRONTING CLIMATE CHANGE: RISK, IMPLICATIONS & RESPONSES* 127-40 (Irving M. Mintzer ed., 1992).

economic stresses. Likewise, many people in urban systems do not have access to clean drinking water or sanitation services, and some 250 million new cases of water-borne diseases are reported each year, resulting in 10 million deaths.⁹ Thus, a major challenge to achieving sustainability will be providing both more water and cleaner water to the growing population.

A. *Multiple Demands, Multiple Consequences*

The demands for and status of water resources reflects interactions across all sectors. For example, the price of energy influences water options, and increases in the cost of energy raise the cost of ground water extraction, pumping, and irrigation operation. In turn, demands on water will influence energy options, for example, through its influence on hydroelectric opportunities or availability of cooling water. Expanding agricultural production, either by increasing yield or the amount of land under production, will carry with it an increased demand for irrigation; at the same time, rapidly urbanizing populations will demand greater water for consumptive purposes, increasing the potential for conflicts surrounding the balance between consumptive and non-consumptive water uses. As more marginal land comes under agricultural irrigation, and more marginal water supplies are used for irrigation, the need to manage for salinity and drainage will intensify, or negative feedbacks to agricultural productivity are likely to occur.

Increased removal of water from surface water systems, whether for agriculture, urban, or industry use, will potentially damage the functioning of the aquatic ecosystems and the marine systems into which they empty, as will effluents from high-density urban environments, industrial by-products, agriculture, and atmospheric deposition of fossil fuel emissions. Competing human demands will lead to a decrease in the amount of water available for natural ecosystems and the species they house, including highly valued lakes, riparian zones, and watersheds. Deforestation and urban developments alter runoff and groundwater recharge patterns. Moreover, pollutants—including nitrate from agricultural fertilization and acidic deposition, metals such as copper, cadmium, zinc, and lead from mining, industrial and agricultural activities, and

9. L. Nash, *Water Quality and Health*, in *WATER IN CRISIS: A GUIDE TO THE WORLD'S FRESH WATER RESOURCES* 25-39 (Peter H. Gleick ed., 1993).

organic pollutants from industrial and agricultural activities—have increased in many of the freshwater and coastal marine ecosystems of the developed world.¹⁰ These problems can be aggravated by human produced climate changes occurring at regional levels.¹¹

B. *Integrated Strategies for Water Management*

Around the world, scientists and policymakers are developing strategies for water use that recognize the interconnected nature of various human activities and the dynamics of natural systems. Many of these attempt to take a watershed perspective, considering water resources in the context of interacting physical, biological, and chemical systems that control water cycling and use at a landscape scale. The watershed perspective takes into account land use, water quality, ecosystem processes and protection, as well as urban and economic requirements. Research on the Chesapeake Bay¹² and the Columbia Basin¹³ provides particularly useful treatments of the challenges involved. Regional water planning seeks an explicit allocation of watershed resources to a variety of water applications, including withdrawals for agriculture, industry, and urban use, as well as in-stream activities such as waste assimilation, ecosystem and species maintenance and preservation, and recreation (Figure 1).

Successful regional water planning will require major changes in the way water is valued, allocated, and managed. For example, regional planning must look seriously at such issues as restructuring agriculture for more efficient water use, dramatically reducing outdoor urban water use and increasing recycling, and determining and providing environmental water requirements.¹⁴ A number of studies have shown that water is

10. *Id.*

11. See Gleick, *supra* note 8; Peter H. Gleick, *Water in the 21st Century*, in *WATER IN CRISIS: A GUIDE TO THE WORLD'S FRESH WATER RESOURCES*, *supra* note 9, at 105.

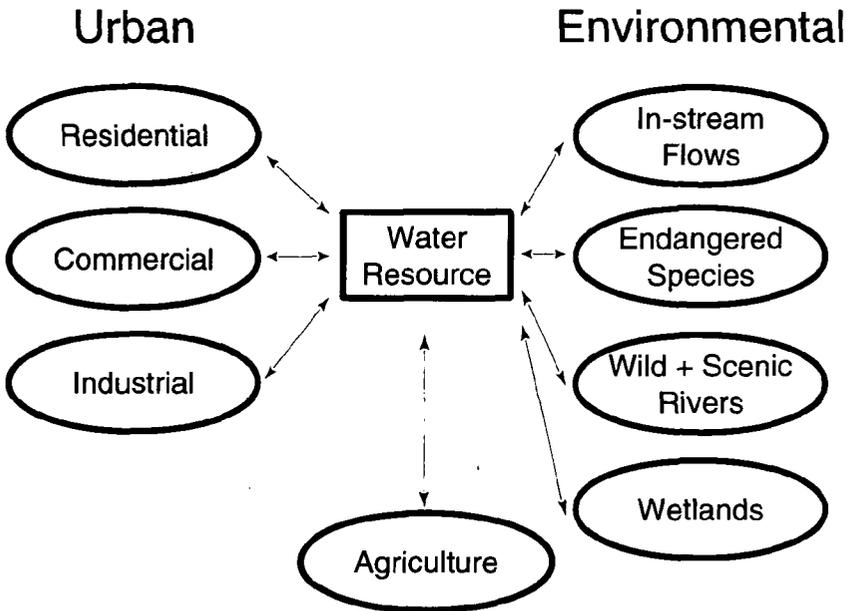
12. E.g. Robert Costanza & Jack Greer, *The Chesapeake Bay and its Watershed. A Model for Sustainable Ecosystem Management?*, in *ECOSYSTEM HEALTH* 261-302 (David Rapport et al. eds., 1998).

13. E.g. Kai N. Lee, *COMPASS AND GYROSCOPE: INTEGRATING SCIENCE AND POLITICS FOR THE ENVIRONMENT* (1993); *COMM. ON PROT. AND MGMT. OF PACIFIC NORTHWEST ANADROMOUS SALMONIDS*, NAT'L RESOURCE COUNCIL, *UPSTREAM: SALMON AND SOCIETY IN THE PACIFIC NORTHWEST* (1996).

14. This is essential for the protection of wetlands, fisheries, and endangered species.

chronically overused because it is underpriced.¹⁵ Pricing policies that reflect the costs of particular uses at particular times and that encourage more efficient use will be crucial. Changes in approaches to water-related regulation, education, laws, markets, and information dissemination also will be necessary. In addition, heightened efforts to transfer available technology to developing regions that potentially lack access are necessary, as are training and institutional arrangements that make their use possible.

FIGURE 1
 WATER RESOURCES ARE REQUIRED FOR MOST HUMAN ACTIVITIES, AND WATER QUALITY IS LIKEWISE AFFECTED BY MANY



In California, the most conspicuous on-going experiment is the CalFed Bay-Delta program,¹⁶ a federally-mandated program that seeks to: (1) provide good water for all users; (2) improve habitats and ecosystem function; (3) resolve the disparities between supply and projected demand; and (4) reduce risks to infrastructure. CalFed is a consortium of two federal agencies,

15. *E.g.* DAVID L. MITCHELL, M. CUBED & W. MICHAEL HANEMANN, CALIFORNIA URBAN WATER CONSERVATION COUNCIL, SETTING URBAN WATER RATES FOR EFFICIENCY AND CONSERVATION: A DISCUSSION OF ISSUES (1994).

16. For more information concerning this program, see <http://calfed.ca.gov/> (last visited Dec. 6, 2000).

ten state agencies, and multiple county agencies, and is thus experimenting not just with marshalling of scientific information, but also with implementing new decisionmaking structures. It is a complex experiment, but one that has the potential to teach us a great deal, regardless of its success or failure in the near-term. The critical point here is that we must study and learn from the CalFed experiment and similar attempts at integrative water planning.

II

ATMOSPHERE

Atmospheric composition and chemistry are influenced by both human activities and natural processes. Emissions associated with industry, fossil fuel consumption, agriculture, and natural ecosystems are linked via atmospheric circulation and chemistry; the consequences of those chemical and physical interactions manifest at local to global scales. In the United States, air quality standards have been in place since the 1950s, yet tens of millions of people still live in areas that do not meet air quality standards. Part of the problem is the complexity of multiple gases from multiple sources mixing in a dynamic atmospheric system.

A. *Multiple Gases, Multiple Sources*

Lessons from the past tell us that we cannot solve air pollution problems without evaluating multiple gases from multiple sources that, together, regulate air chemistry and pollution. In the case of urban smog in the United States, for example, a decade or more of regulating hydrocarbons emissions from industrial processes failed to improve air quality; regulation of the nitrogen oxides emitted from automobiles is now seen as an additional critical factor in controlling pollution.¹⁷ Moreover, while we once thought of smog and tropospheric ozone production as an urban-scale phenomenon, it is now clear that it can be regional or even global in scale. For example, studies in the southeastern United States have indicated that urban emissions of hydrocarbons and nitrogen oxides in conjunction with nitrogen oxide emissions from the agricultural sector and

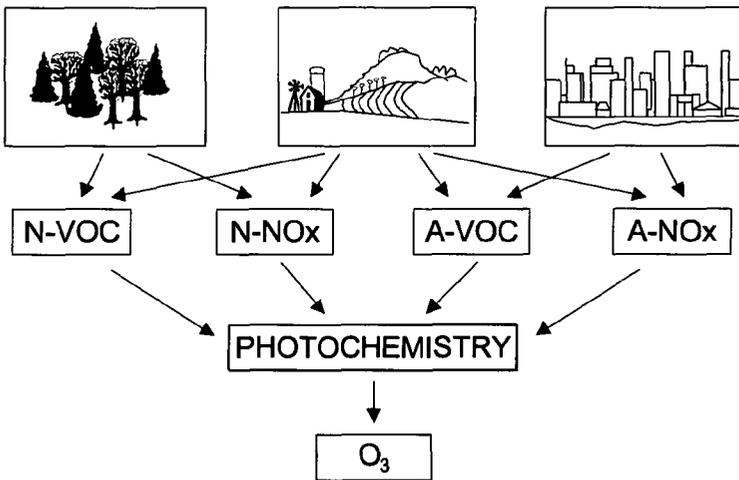
17. PANEL FOR COLLABORATIVE RESEARCH SUPPORT FOR AID'S SUSTAINABLE AGRICULTURE, NATIONAL RESOURCE COUNCIL, TOWARD SUSTAINABILITY: A PLAN FOR COLLABORATIVE RESEARCH ON AGRICULTURE AND NATURAL RESOURCE MANAGEMENT (1991).

hydrocarbon emissions from natural forests combine to affect regional-scale pollution events (Figure 2).¹⁸ Such extensive pollutant levels may feed back to reduce agricultural productivity¹⁹ and impair human health and the health of natural ecosystems at local and regional levels.

Scientists now recognize that atmospheric changes, once characterized as local to regional in scale, actually contribute to global atmospheric and climatic change. Sulfur aerosols emitted from a variety of combustion processes are a source of regional acid deposition and have been under regulation for the last 30 years. Only recently have researchers suggested that those aerosols that form regionally may result in an increase in Earth's reflectance, thereby offsetting some of the effects of greenhouse

FIGURE 2

STRATEGIES FOR SMOG AND TROPOSPHERIC OZONE CONTROL MUST TAKE INTO CONSIDERATION BOTH NATURAL BIOGENIC VOLATILE ORGANIC CARBON (N-VOC) AND NITROGEN OXIDES (N-NO_x) ORIGINATING FROM VEGETATION AND SOILS AS WELL AS ANTHROPOGENIC SOURCES OF THE GASES (A-VOC AND A-NO_x)²⁰



gas increases.²¹ Similarly, burning associated with land use changes such as deforestation or agriculture, alone or in

18. See W. L. CHAMEIDES & ELLIS B. COWLING, *THE STATE OF THE SOUTHERN OXIDANTS STUDY: POLICY-RELEVANT FINDINGS IN OZONE POLLUTION RESEARCH 1988-1994* (1995).

19. W. L. Chameides et al., *Growth of Continental Scale Metro-Agro-Plexes, Regional Ozone Pollution and World Food Production*, 264 *SCI.* 74, 77 (1994).

20. Figure adapted from CHAMEIDES & COWLING, *supra* note 18.

21. See INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, *CLIMATE CHANGE 1995: THE SCIENCE OF CLIMATE CHANGE* (J. T. Houghton et al. eds., 1996).

combination with industrial air pollution, can have tremendous impacts on the health of people and ecosystems. Fires associated with tropical deforestation emit carbon, nitrogen, and sulfur gases into the atmosphere, where they undergo chemical reactions and lead to the production of tropospheric ozone and acidic precipitation. Consequently, people and ecosystems far removed from urban activity experience high ozone episodes and acid rain.

B. Integrated Strategies for Atmospheric Resources

As with water resources, managing air quality and the atmospheric environment requires a different strategy than we have seen in past decades. Such a strategy must account for the multiple sources of materials released into the atmosphere, the natural and human-influenced processing of those materials, and the multiple and interacting effects on exposed systems. In the case of the atmosphere, the scale at which this integrated management must take place ranges from an urban airshed to the globe.

For example, in the case of tropospheric ozone in the southeastern United States, referred to above, regionally-based implementation strategies that control emissions across large regions are being developed with input from the Southern Oxidant Study (SOS).²² The SOS provides multi-disciplinary, multi-scale information on the emissions, atmospheric meteorology and chemistry, and consequences of ozone and other pollutants in the airshed. Use of such information in management, however, requires that consortia of local, state, and national agencies, industries, and scientists come together to develop research and management programs with longer time horizons and greater spatial domains.

III

INTEGRATED STRATEGIES FOR MULTIPLE AND INTERACTING ENVIRONMENTAL ISSUES

Programs of integrated, regional-scale water and air resource plans are being developed and used all over the world. Likewise, conservation planners and practitioners are also experimenting with integrated conservation and development programs that preserve ecosystems and species within them at the same time that they foster regional economic development. When

22. CHAMEIDES & COWLING, *supra* note 18.

successful, these integrative approaches provide examples of management in which human societies and "nature" are both winners. Not all of them are successful, however, and we stand to learn as much from the failures as from the successes.

But I believe that we need to take a further step in an integrative, place-based analysis. We need to look not just at independent water, air, or ecosystem issues, but at how all of these issues interact. Why? Because anthropogenic changes are occurring in all of these resources at the same time, and solutions directed toward one could inadvertently and negatively affect another. For example, strategies that focus on solving air pollution problems could inadvertently negatively affect water, as we have seen in California's experience with the gasoline additive MTBE.

Unfortunately, integrative, place-based analysis that deals with multiple and interacting changes is something we *do not know how to do*. In this final section, drawing on work that I and a group of collaborators have been doing in the Yaqui Basin in Sonora, Mexico, I will describe a situation that argues strongly for such an integrative approach.

Located in northwestern Mexico, between the Sea of Cortez and the Sierra Madres, the Yaqui Valley incorporates 250,000 hectares of irrigated wheat agriculture. It is the home of the Green Revolution for wheat.²³ Over the past 40 years, the steady supply of improved wheat varieties along with subsidized water and fertilizers has led to dramatic increases in wheat yields.²⁴ In our previous studies in the valley, we have found that fertilizer and water use lead to substantial losses of nitrogen in various forms, including the greenhouse gas nitrous oxide, the air pollutant NO_x, and the water pollutant nitrate.²⁵ We also studied the national and international policies that have determined agricultural practices in the valley and the economic determinants of decisions at the farm scale.²⁶ Finally, we

23. R. L. NAYLOR, W. P. FALCON, & A. PUENTE-GONZALEZ, INTERNATIONAL MAIZE AND WHEAT IMPROVEMENT CENTER (CIMMYT), POLICY REFORMS AND MEXICAN AGRICULTURE: VIEW FROM THE YAQUI VALLEY (forthcoming 2001).

24. See *id.*

25. See P. A. Matson, R. Naylor & I. Ortiz-Monasterio, *Integration of Environmental Agronomic, and Economic Aspects of Fertilizer Management*, 280 SCI. 112, 115 (1998); W. J. Riley & P. A. Matson, NLOSS: A Mechanistic Model of Denitrified N₂O and N₂ Evolution from Soil, 165 SOIL SCI. 237 (2000); J. A. Panek et al., *Distinguishing Nitrification and Denitrification Sources of N₂O in a Mexican Wheat System Using ¹⁵N*, 10 ECOLOGICAL APPLICATIONS 506 (2000).

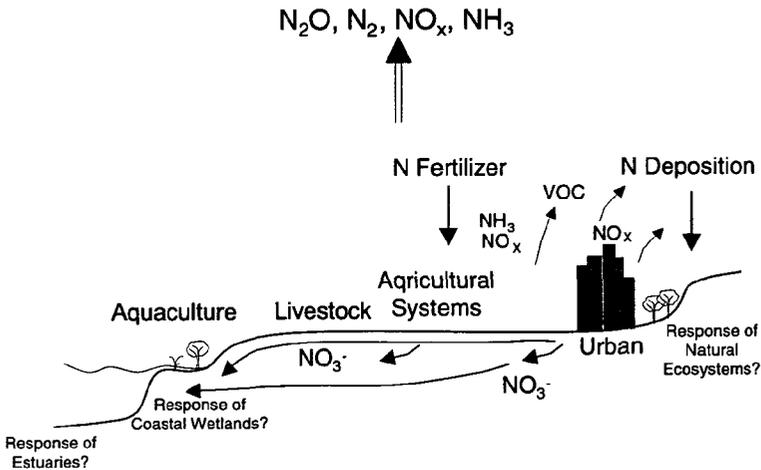
26. See NAYLOR, FALCON, & PUENTE-GONZALEZ, *supra* note 23; Matson, Naylor & Ortiz-Monasterio, *supra* note 25.

evaluated alternatives to the typical fertilizer management regimes that are economically feasible, agronomically sensible, and environmentally beneficial.

In many ways, we have studied the agricultural system as an isolated system, albeit in an interdisciplinary way. But what is done there is inextricably linked to downwind and downstream ecosystems, through transfers of materials such as various forms of nitrogen or other pollutants in air and water (Figure 3), by the movement of plants and animals, and by various human actions. Moreover, water allocation and fertilizer use decisions in the agricultural fields of the Yaqui lead to effects that interact with urban and industrial emissions; together, all of these activities will affect both downstream and downwind systems, with consequences for coastal wetlands, fisheries, deserts, and

FIGURE 3

FLUXES OF ACROSS LINKED UPLAND AND MARINE ECOSYSTEMS. NITROGEN IS APPLIED TO AGRICULTURAL FIELDS AS FERTILIZER; A PROPORTION (OFTEN 50%) LEAVES FIELDS IN THE FORMS OF NITRATE (NO_3^-) WHICH LEACHES TO SURFACE AND GROUNDWATER SYSTEMS; NO_x OR NH_3 GASES REACT WITH URBAN POLLUTANTS (VOC AND NO_x) IN THE ATMOSPHERE AND ARE DEPOSITED DOWNWIND; AND N_2O , A GREENHOUSE GAS



other natural ecosystems of Sonora. The consequences of agriculture here interact with those of urban and industrial growth as well as land use change in the coastal and upland systems. To understand one set of effects, we must understand them all. If we are interested in wetland conservation, for example, we must pay attention to aquaculture development in the coastal zone but also to fertilizer overuse and water allocation in the upstream region.

How can we study and manage this as a linked system? Can we understand how the system works and predict how vulnerable it is to changing policies, climate change, or other external forces? Probably not yet, given that we need to understand the interacting human and biophysical dimensions of the system. We have satellite imagery to help us understand connections and directions of change across this landscape. We have computational ability to evaluate complex systems. And we have a new generation of researchers who want to, and are trained to ask interdisciplinary and multidisciplinary questions. What is missing is the research support to carry out this kind of complex evaluation and to conduct management experimentally and adaptively.

But even with such information, are institutions in place to make use of it? Here, a consortia of local, state, and national agencies, industries including agribusiness and fisheries, landowners, urban dwellers, NGOs, and scientists must work together to develop and implement regional plans. They will have to be concerned not just with water or air or living resources, but with the interaction of all of these systems.

CONCLUSION

This Article illustrates the strong linkages and interactions that exist between resources and human activities across many different issues and sectors. Efforts to reach the goal of environmental sustainability cannot be expected to succeed if they are pursued within narrow disciplinary or sectoral frameworks that ignore these interactions. Rather, society and its decisionmakers must recognize that agricultural, urban, industrial, and ecosystem processes interact with each other and must be evaluated as place-based integrated systems. This is a major conclusion of *Our Common Journey*,²⁷ and it is shared with other groups that have addressed analogous questions in recent years, including the *World in Transition* reports of the German Advisory Council on Global Change.²⁸ To move forward, we will need a research and development structure that allows and encourages the accounting of linkages among all sectors and that takes advantage of those inter-linkages in a regional research, planning, and problem solving context.

27. OUR COMMON JOURNEY, *supra* note 3.

28. GERMAN ADVISORY COUNCIL ON GLOBAL CHANGE, *WORLD IN TRANSITION: THE RESEARCH CHALLENGE* (1997).