



Linking global and local scales: designing dynamic assessment and management processes

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Abstract

This paper identifies challenges inherent in addressing multi-scale environmental problems, and outlines tentative guidelines for addressing such challenges and linking science and policy across scales. The study and practice of environmental assessment and management increasingly recognize the importance of scale and cross-scale dynamics in understanding and addressing global environmental change. These ongoing efforts, however, lack a systematic way of thinking about and addressing the challenges involved in integrating science and policy across multiple scales, for example, in the design of policy-relevant, scientific assessments of problems such as climate change. These challenges include matching scales of biogeophysical systems with scales of management systems, avoiding scale discordance (matching the scale of the assessment with the scale of management), and accounting for cross-scale dynamics. In this paper we propose tentative guidelines for meeting such challenges for both assessors and decision-makers: (1) utilize boundary organizations — institutions which serve to mediate between scientists and decision-makers, and between these actors at different scales; (2) utilize scale-dependent comparative advantages — coordinating the allocation of resources, technical expertise, and decision-making authority to best capitalize on scale-specific capabilities; and (3) employ adaptive assessment and management strategies — constructing long-term, iterative, experiment-based processes of integrated assessment and management. © 2000 Elsevier Science Ltd. All rights reserved.

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1. Introduction

How might a scientific assessment of global environmental change which is able to influence local decision-making be structured? Who should be involved in such an enterprise to assure scientific credibility, practical relevance, and political saliency among its audience? How should authority and responsibility to assess and manage global environmental problems be apportioned among different levels of government? The needs underlying these questions share the implicit or explicit recognition that global environmental changes are cross-scale phenomena that require assessment at all scales and

integration across scales in order to inform policy- and decision-making most effectively.

The study and practice of environmental assessment and management increasingly recognize the importance of scale and cross-scale dynamics in understanding and addressing global environmental change. In the arena of climate change, for example, the climate science community has a growing interest in obtaining *local*-scale data that can increase the accuracy and predictive capabilities of *global* climate models. Inversely, scientists are also responding to the demand of policy-makers to assess potential *local* impacts of *global* climate change and to produce policy-relevant information that can be used at *regional* and *local* scales. Moreover, decision-makers from the *local* through *global* scales are attempting to understand how mitigative and adaptive actions at one scale might constrain or provide opportunities at other scales (Alcamo et al., 1996; Intergovernmental Panel on Climate Change, 1996, 1998; Miller et al., 1996; Easterling, 1997; Lins et al., 1997; Wilbanks and Kates, 1999).

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What is missing from these ongoing efforts, however, is a systematic way of thinking about and addressing the challenges involved in integrating science and policy across multiple scales, for example, in the design of policy-relevant, scientific assessments of problems such as climate change. This paper develops tentative guidelines for designing such assessments based on empirical and theoretical work conducted by the authors. While we focus primarily on long-term climate change in this paper, multi-scale challenges also characterize issues like El Niño/Southern Oscillation events, acid precipitation, biodiversity loss, and a wide range of other environmental and natural resource problems.¹

Relying on a range of applied and theoretical literatures, as well as on our own research on the implications of climate change for water management in the US agricultural sector and for US coastal zone management, we identify three broad categories of challenges for management and assessment efforts which address global environmental change: (1) matching the scales of the biogeophysical system and the management system — an institutional fit problem; (2) matching the scales of the assessment and the management system — a scale discordance problem; and (3) understanding the linkages between scales, and how they affect decision-making, information flows, and the integration of information into the decision-making process — a cross-scale dynamics problem.

Throughout the remainder of this paper we will use these challenges to guide our conceptual discussion of scale and cross-scale dynamics in assessment and policy-making (Section 2), and to develop a set of tentative guidelines to think more systematically about how assessment and management can more consciously address scale and cross-scale interactions (Section 3).

¹ Scientists studying El Niño/Southern Oscillation (ENSO) events are broadening efforts to understand and forecast local impacts and teleconnections (dynamic, systematic linkages across large distances via the atmosphere and oceans). Meanwhile, international weather institutions such as the World Meteorological Organization (WMO), are struggling with how to make these assessments relevant and useful for national and sub-national decision-makers (Glantz, 1996; Glantz et al., 1997; Orlove and Tosteson, 1999). In the evolution of emissions and transport models used in the continuing negotiations for the Long-Range Transboundary Air Pollution (LRTAP) convention, assessors and policy-makers endeavor to understand the influence of international obligations on national implementation, and conversely, to understand the role of national and local actions in large-scale patterns of pollution distribution (Levy, 1994; Tuinstra et al., 1999). In current debates over the implementation of the Convention on Biological Diversity, negotiators are struggling with how to assess and construct policy options which address the global goal of biodiversity conservation while preserving acceptable national sovereignty over biological resources and information (Raustiala and Victor, 1996).

2. Challenges for policy-relevant assessment of multi-scale environmental problems

We begin this discussion by clarifying the fundamental concepts we use. For the purposes of this paper, “scale” refers to any specific geographically or temporally bounded level at which a particular phenomenon is recognizable. “Scale” can also — and sometimes simultaneously — imply a level of organization or a functional unit (Ahl and Allen, 1996). We recognize that there is reasonable disagreement on the precise extent or definition of any scale (e.g., where are the boundaries of something “local?”), and that there rarely is perfect congruence of, for example, a spatial and a functional unit identified at the same scale (Clark, 1987; Sayer, 1991). This variance is evidence of how scale is socially defined, and particular to certain political, scientific, legal, or cultural lenses. People impose a definition of scale for a particular issue and for particular purposes. As such, scale is a heuristic employed by scientists and managers to organize their understanding of the world and the relationships and interactions therein (e.g., ecologists find it useful to think of trees, forests, and biomes; politicians find it useful to think of cities, counties, states, and nations). In fact, because scale is largely socially constructed, the conceptualization of scale brought to any specific case by particular players is mutable and amenable to adaptation so as to best fit the management of the environmental problem at hand. For example, the ongoing regional component of the US National Assessment of Climate Variability and Change has divided the country into 18 regions. The resulting scale at which each region is assessed is critical to the content, tools, and outcomes of the assessment, yet can be changed in future assessments if deemed inappropriate.

Scale is but one attribute which can guide the examination of global environmental problems, yet in this paper we argue that the understanding of, and responses to, global environmental problems will continue to be hampered by inefficiencies and unnecessary obstacles if we do not consciously and systematically address the multi-scale nature of biogeophysical and human systems and the interactions between them across scales. We use climate change as an example to briefly elaborate on this multi-scale nature of environmental problems.

As a biogeophysical phenomenon, climate change occurs over a continuous range of spatial and temporal scales. For example, complex biochemical processes govern the decomposition of plant matter lying on a deforested tract of Amazonian rainforest, releasing carbon dioxide into the atmosphere. Once released to the atmosphere, molecules of carbon dioxide rapidly merge into a uniform global mix of gases regulating the Earth’s atmosphere. The composition of the atmosphere, and its resultant impacts on climate and weather influence local-scale phenomena, such as decomposition rates.

Any global, systemic changes are thus linked to, and controlled by, the complex result of local processes and vice versa. Natural scientists have found that the conceptual use of scale has contributed to insights about the structure and function of these linked processes (Rosswall et al., 1988; Levin, 1992; Keitt et al., 1997; Levin et al., 1997).

The scale lens can also be used to examine the social phenomena and processes underlying climatic change which roughly correspond with characteristic spatial scales, ranging from individuals to households to states or provinces to the population of nations or the world. In addition to this demographic perspective, social scales can also be defined as clearly bounded and organized political or functional units (e.g., cities, counties, states or provinces, and nations) with linkages between them being created by constitutional, statutory, or other social means. The linkages between social phenomena at different scales are made complex, however, by the fact that people are also connected via non-governmental institutions and social networks that are less strongly correlated with spatial scales — e.g., through markets and industries, clans, religions, professions, or voluntary associations (Sabatier and Jenkins-Smith, 1993; Ostrom, 1998; Keck and Sikkink, 1999).

Finally, the relationships *between* social and biogeophysical entities can also be examined in scale-specific ways. For example, the impacts of coastal storms can be bounded in terms of shorefront properties, coastal communities, a state's coastline, or an entire continent's vulnerable seaboard. Similarly, the emissions of greenhouse gases and their influence have been viewed at the scale of individual power plants, industrial sectors, and impacted regions, nations, or subnational entities (Wilbanks and Kates, 1999).

Indeed, political institutions or assessment efforts organize (and become identified) at different scales in part to manage problems that are seen as being highly relevant at a particular scale. For example, while greenhouse gas abatement is approached foremost at the global/international scale, issues of vulnerability to climate change impacts, like water shortage or sea-level rise, are primarily assessed at national or regional scales. The complexity of these cross-scale human–environment relationships is also illustrated by returning to the example of carbon release in the Amazonian rainforest. Global market forces and Brazilian national economic and development policies influence local rates of deforestation, and thus local release of carbon dioxide. This local release contributes to global climate change (with heterogeneous local impacts), which is being addressed politically through international negotiations involving representatives of the Brazilian national government.

Over time, climate change has been looked at through a variety of useful lenses — biochemical, geophysical,

socio-economic, sectoral, political and technological. Each has yielded its special insights into the complexity of the climate change issue. Through our research, however, we have identified three problems that are missed by those perspectives because they pay little attention to the multi-scale nature of the problem: scale mismatch between environment and management; scale mismatch between assessment and management; and ignorance of cross-scale dynamics. We propose the scale lens as an important additional heuristic to explore and explain some of the challenges that assessors and policy-makers face as they struggle to produce and use credible and salient scientific information. We turn to these challenges below.

2.1. Scale mismatch between environment and management — an institutional fit problem

The boundaries of property and government, like the less sharply etched patterns of markets, rarely follow the outlines of biology and topography. (National Research Council, 1996b, p. 326)

The problem of matching the scales of the biogeophysical system and the management system is perhaps the most thoroughly studied of the three challenges we highlight. The problem arises when an environmental phenomenon is managed at an institutional scale whose authoritative reach does not correspond with the geographical scale or particular spatial dynamic of the environmental problem. The challenge for management regimes is to avoid policy pathologies which emerge because environmental and human systems “proceed at [their] own pace and in [their] own space, and that creates extraordinary conflicts when ecosystems, institutions, and societies function on scales that are extremely mismatched” (Holling, 1995, p. 73). The result is often unsustainable management of the resource (Lee, 1993; Folke et al., 1998).

Two illustrative cases demonstrate where underlying institutional structures drive this kind of scale mismatch problem. In the first, an environmental problem is exported beyond certain jurisdictional boundaries to neighboring jurisdictions which have no or little influence over the source of the problem — the case of environmental externalities (Holland et al., 1996). This is seen, for example, in classic pollution problems such as transboundary transport of acidifying compounds, or water pollution in a watershed that crosses political boundaries.

The other case includes the classic “tragedy of the commons” problem (Hardin, 1968), frequently discussed in the common-pool resources literature. It is argued, for example, that the proper management of common-pool environmental resources depends on centralized (higher-scale) control and management and/or on coordinated

collective action and the establishment of institutionalized norms and rules for behavior (Hardin, 1982; Ostrom, 1990; Bromley, 1992). Examples include the management of underground aquifers, ocean fisheries, or sediment budgets in littoral systems. In recent years, the atmosphere has come to be framed as a global commons as well.

With increased understanding of transboundary and common-pool resource management challenges, and often in response to spectacular management failures, both governmental and non-governmental activities have been undertaken to address these scale mismatch problems. From the late 1970s through the passage of the US Clean Air Act Amendments in 1990, for example, tropospheric ozone pollution moved from a local issue to one which involved regional consortia and collaborative efforts of multiple state and local actors under federal guidance (Portney, 1990; Keating and Farrell, 1999). Trends in water resource management also exhibit this shift. Increasingly, water issues are dealt with on the scale of watersheds, with collaboration across political jurisdictions (Francis and Reiger, 1995; Rabe and Zimmerman, 1995).

Despite these changes, however, scale mismatch continues to be an endemic problem. For example, even though the US has century-long demographic records at various jurisdictional levels, its population data cannot be retrieved (and thus analyzed) easily for units at the scale of coastal watersheds or floodplains. This example is just one of many which draws attention to the importance of understanding the mechanics of matching the scales of human management systems to the scales of physical systems (Holling, 1995; Folke et al., 1998).

2.2. Scale mismatch between assessment and management — a scale discordance problem

As climate change matures both as a scientific and as a political issue, and as policy-makers increasingly want assessment results to enter into policy- and decision-making, the problem of scale discordance is becoming ever more prominent.

Resource planners and managers interested in utilizing climate model output as part of their operational activities immediately confront the dilemma of scale discordance. Their functional responsibilities cover relatively small geographical areas and necessarily require data of relatively high spatial resolution. Climate models cover a large geographical, i.e., global, domain and produce data at comparatively low spatial resolution (Lins et al., 1997, p. 63).

Essentially, the discordance is between the scale of scientific analysis and assessment and the scale for which

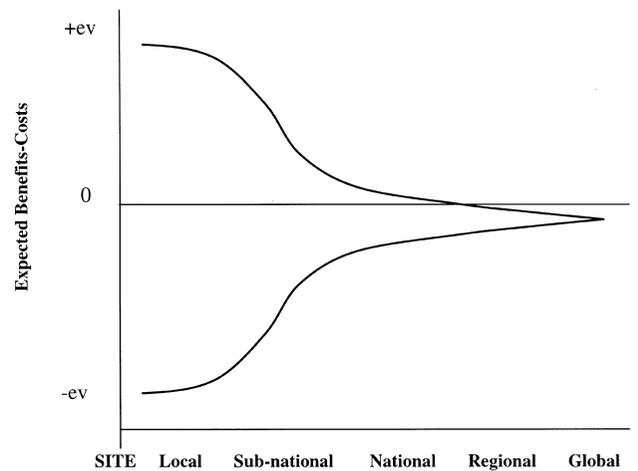


Fig. 1. Scale-dependent distribution of impacts: Effects of geographic/economic scale on net gain (benefits minus costs) arising from effects of environmental change on society. (adapted from *The Canada country study: climate impacts and adaptation, national summary for policy makers* (Environment Canada, 1997)).

scientific information is needed to usefully inform management. This challenge is illustrated in Fig. 1, in which the impacts of a global environmental risk, like climate change, are plotted as a function of scale. At large scales, where assessments might aggregate social welfare, the *overall* impacts (costs) of climate change are relatively small. Assessments which focus on more local scales, however, reveal an underlying pattern of widely ranging costs and benefits, with some large winners and some large losers (Environment Canada, 1997). In this case, assessments which are undertaken at large scales of analysis might have little to offer to managers at smaller scales, who might be primarily concerned with the distributional effects of global climate change. These managers need analyses with greater resolution, one that can disaggregate costs and benefits. Inversely, assessments which focus solely on local-scale impacts might not be useful to policy-makers at higher scales who might be ultimately interested in aggregate social welfare. This discordance illustrates why decision-makers and resource managers increasingly demand that assessments be scaled up or scaled down, whichever is appropriate (Wessman, 1992; Lins et al., 1997; Schubert, 1997; Harvey, 2000).

The need to scale up and down between the global and the local in order to address data resolution needs is evident in, but not limited to, three related trends in climate change science and policy. The first is seen in the efforts to identify patterns of contributions to greenhouse *forcing* at various, and increasingly smaller, scales. The goal of this effort is to better characterize and understand causal relationships between local human behavior, greenhouse gas emissions, and global climate change,

and to establish a reliable accounting system for emission reductions which is key to more successful international climate negotiations (Intergovernmental Panel on Climate Change, 1996; Wilbanks and Kates, 1999; Harvey, 2000). The second trend is driven by both climate scientists and national and subnational policy-makers who wish to better identify, understand, and predict smaller-scale environmental and socio-economic *impacts* of climate change (MINK Project, 1991; Office of Technology Assessment, 1993; Environment Canada, 1997; Lins et al., 1997; Intergovernmental Panel on Climate Change, 1998). Third, interests within the science and policy communities have recently shifted to focus on *adaptation* responses to global climate change, and the ultimately local nature of such responses (Environment Canada, 1997; US Global Change Research Program, 1999).

Despite this increasing demand for down-scaled models of climate change and rapid improvements in computer technology and scientific understanding, assessors have not been able to keep up with the growing demand for more useful, higher-resolution models and data (Kattenberg et al., 1996; Easterling, 1997; Houghton et al., 1997; Shackley et al., 1998). Thus, the problem of scale discordance persists and has become more pressing in the light of the political interest of national and sub-national governments and of the private sector to respond to climate change.

At least three problems ensue from persistent scale discordance. The first is that explanations and predictions of climate change lack credibility for regional and local decision-makers. Assessors are unable to predict impacts at local scales, and can therefore say nothing definitive and credible about local impacts. This lack of local specificity often leads to a complementary lack of credibility about what assessors say about climate change in general. This skepticism is compounded by the fact that assessment efforts which only produce outputs of large-scale impacts rarely provide local decision-makers with the tools to use that kind of output. The second problem is the dearth of *relevant* outputs that are useful to and useable by regional and local decision-makers. Without local specificity and detail, the issue at hand lacks salience and decision-makers are unable to either understand the potential impacts of climate change, or formulate scale-appropriate adaptive responses (Easterling, 1997; Lins et al., 1997). Finally, decision-makers always face situations in which decisions are made under conditions of uncertainty. In the case of climate change, science may not be able to supply the desired resolution of climate information in the near future. In the meantime, decision-makers must find the types of policies and management strategies for which scale-specific, adequate information already exists. This may imply, for example, early institution of

enabling policies or insurance schemes at higher scales while postponing specific adaptation actions at the local scale.

2.3. *Accounting for linkages between different scales — a cross-scale dynamics problem*

Though the multi-scale nature of environmental problems has in some cases been acknowledged, and efforts have been made to match scales of problem and management, science and policy-making often pay most attention to just one of the relevant scales of a problem, thereby missing important *cross-scale* interactions — *those in which events or phenomena at one scale influence phenomena at other scales* (Holling, 1978, 1986, 1995; O'Neill, 1988; Gunderson et al., 1995; Gibson et al., 1997; Peterson and Parker, 1998). “Where global change is concerned, it can be argued that a focus on a single scale tends to emphasize processes operating at that scale, information collected at that scale, and parties influential at that scale — raising the possibility of misunderstanding cause and effect by missing the relevance of processes that operate at a different scale” (Wilbanks and Kates, 1999, p. 8).

This challenge is illustrated, again, in Fig. 1. If global change is assessed at only one scale, and thus only one characterization of the distribution of costs and benefits is analyzed, a more complete picture of the underlying structure of impacts is foregone. Thus, little is learned about how the distribution of costs and benefits at one scale influences and is linked to available political response strategies at other scales.

Hierarchy theory offers one approach to explore these linkages in biogeophysical and social systems. It facilitates the ordered examination of complex systems by disaggregating them into *interacting* processes and structures at different scales (Simon, 1962; Allen and Starr, 1982; Salthe, 1985; O'Neill, 1988). Its central idea is that a phenomenon at a chosen scale of interest is the synergistic result of both the smaller/faster dynamics of system components at the next lower scale and the constraints imposed by the generally slower/larger system dynamics at the next higher scale. The only way that the system can be meaningfully understood at any one scale is to simultaneously capture the driving and constraining forces at both lower and higher scales (Pattee, 1973; Holling, 1978, 1986, 1995; O'Neill, 1988). For example, in order to understand regional precipitation patterns, it is necessary to understand large-scale climatic forces as well as local-scale topographic characteristics. Similarly, to understand the sediment budget of a coastal segment, one needs to understand the larger regional constraints on sediment sources and sinks, but also the local coastal geomorphology and nearshore bathymetry, tidal and other currents, atmospheric conditions affecting sediment movement,

and other small-scale (e.g., human) influences on the sediment system.

While issues of cross-scale dynamics in social systems have not been as thoroughly examined as in natural systems (Gibson et al., 1997), analyses of federalist systems of governance by political scientists, economists, legal scholars, and political economists have illuminated the links connecting different scales in hierarchical political or decision-making systems. The federalist literature examines, for example, how governmental (i.e., legislative, regulatory, monitoring, or information-producing) actions that occur at one scale influence the suite of actions available to, or mandated by, decision-makers at other scales (Percival, 1995; Holland et al., 1996). As in the case of complex natural systems, research in federalism maintains that in order to understand political behavior at any specific scale, it is important to understand the various political, economic, and social drivers and constraints at neighboring scales. Thus, for example, to understand water policy and management on the scale of a state, it is critical to understand the context of federal regulations and water-related assessment efforts, as well as local water-use practices and regulatory regimes. Examining such cross-scale dynamics frequently entails the difficult challenge of integrating knowledge produced at these respective scales which might be characterized by quite disparate methodologies and disciplinary approaches.

Finally, there is little understanding of what the cross-scale interactions in both human and environmental systems mean for the movement of information across, and the differential needs for knowledge at, different scales. The traditional approach to incorporating scientific information into the policy process has been to produce scientific assessment reports and then to funnel them to policy-makers — an approach we caricature as the pipeline model of information dissemination. This model is particularly common in the top-down approach to the provision of policy-relevant scientific information about multi-scale problems in which it is presumed that science produced at a higher scale (e.g., a national report) will be assimilated and used “as is” at lower scales (e.g., by states or municipalities) (Lindblom, 1990; Kingdon, 1995). One fundamental problem with this approach is that it ignores the *interactions* between actors located at different scales. It is critical for the design of assessment and outreach processes, for example, to understand how coastal scientists conducting global analyses of sea-level rise interact and communicate with scientists studying local impacts of that process, and what kind of credibility each has with the other; or how national coastal assessors interact with coastal zone managers and public and private decision-makers at the state or local scale (e.g., how credible they are or how research and assessment agendas are set); or in what format, frequency, and style information is needed and commu-

icated to be most useful to decision-makers located at different scales.

3. Tentative design guidelines for assessment and management of multi-scale environmental problems

The fundamental challenges outlined above are faced by the producers and users of assessments when addressing multi-scale environmental problems. Below we build on both the theoretical advances made regarding these challenges and on our own (Cash, 1998; Moser, 1998) and others' empirical research to propose three broad design guidelines for assessments of cross-scale environmental problems. We also discuss the choices and trade-offs they entail. In essence, we provide a framework of hypothesized attributes of effectively integrated information and decision systems.

3.1. Utilize boundary organizations

In thinking systematically about the interface between science and policy in the assessment process, we draw on the science studies literature which conceptualizes this interface, not as a sharp line or demarcation, but as a fuzzy, dynamically shifting and jointly created and maintained *boundary* (Jasanoff, 1987, 1990; Gieryn, 1995). This boundary is negotiated, contested, and maintained by both scientists and decision-makers as they struggle to resolve a fundamental tension that emerges when science is brought into the policy arena: maintaining scientific credibility while assuring political saliency (Jasanoff, 1987, 1990). *Boundary organizations*, institutions that straddle and mediate the divide between science and policy, are established to help in this task (Guston, 1999).

The concept of boundary organizations is used in the science studies literature only in the context of the science/policy interaction, but it is equally useful for describing the boundaries between different scales or functional levels (Cash, submitted). In this application, boundary organizations serve to mediate between scientists and decision-makers on the one hand, and between these actors at different scales on the other (Fig. 2). Thus, the conceptual model of boundary organizations provides a powerful alternative model to the pipeline model of transfer and use of scientific information. In the boundary organization model, rather than being passive recipients of information, decision-makers are involved in the creation and maintenance of the relationship with scientists, the science-policy boundary, and the scientific and technical outputs. As opposed to the unidirectional flow of information in the pipeline model, boundary organizations facilitate the multi-directional flow of information (i.e., needs, output format, results, etc.) between science and decision-making and across scale.

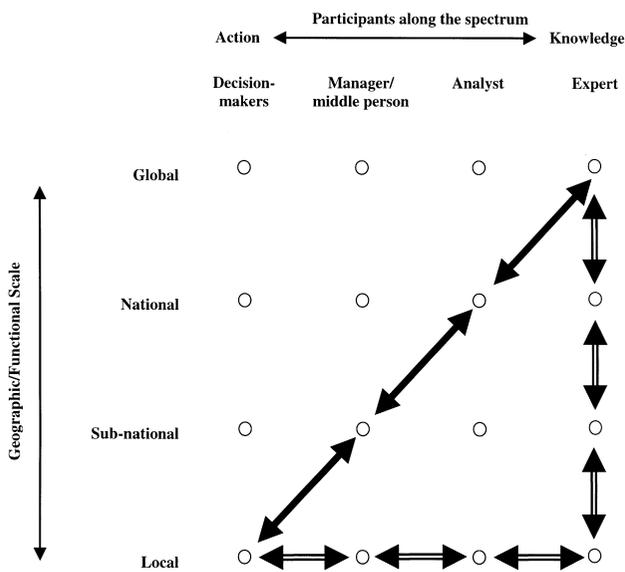


Fig. 2. Assessment/Management Heuristic: This two-dimensional heuristic can be used to map various pathways of cross-scale and science-policy collaboration and communication. The bi-directional arrows indicate stylized pathways of interaction among different actors in an assessment/management process. The circles indicate positions or roles common in assessment and management systems which can be occupied by individuals or institutions. They are socially constructed and shift in location and responsibilities. Boundary organizations can also occupy one of those positions (circles), or the spaces between them, and their function is to maintain and facilitate both the connection and separation across boundaries (see text for further explanation). Two hypothetical pathways (black arrows and open arrows) are illustrated above. Note that any one actor or institution may occupy more than one position in this stylized scheme.

From a normative perspective, boundary organizations may be considered essential elements of a cross-scale assessment design in which either existing or new boundary organizations are engaged. They serve to resolve the tension between policy and science described above, and they facilitate the convergence of interests, ideas, disciplinary languages and perspectives at different scales. Boundary organizations can accomplish this, for example, by producing outputs (referred to as *boundary objects* in the social studies of science literature) that are valued on both sides of the boundary and provide a site for cooperation, debate, evaluation, review, and accountability (Star and Griesemer, 1989; Guston, 1999). Examples of such outputs include reports (e.g., Intergovernmental Panel on Climate Change reports), models (e.g., the Regional Air Pollution Information and Simulation, or RAINS, model, used in the negotiation of the Convention on Long-Range Transboundary Air Pollution in Europe), forecasts (e.g., ENSO predictions), or newsletters (e.g., the *Pacific ENSO Newsletter* produced by the Pacific ENSO Application Center). Boundary organizations have been enrolled to mediate across

boundaries for a wide range of environmental and natural resource issues.²

As intermediary institutions, boundary organizations can provide an array of important functions (Guston, 1999; Cash, submitted; Moser, submitted). We illustrate five of these functions by using the Cooperative State Research, Education, and Extension Service of the US Department of Agriculture (CSREES) as an example (Youmans et al., 1988; Rasmussen, 1989; National Research Council, 1996a; Cash, submitted).

(1) *Information brokerage* — “*translating*” *scientific information across scales as a “boundary spanner”* (Leifer and Delbecq, 1978): One fundamental component of the CSREES is the county extension office. Extension agents³ within these offices act as information translators, acquiring both basic and applied research from state agricultural colleges,⁴ CSREES regional research and experiment stations, USDA research facilities, and private industry, and packaging it in ways that are usable by farmers or local elected officials.

(2) *Communication of salient research needs to scientists*: Each county has an elected or voluntary committee of citizens who regularly suggest research and program concerns to county agents who then communicate these items to state and USDA researchers. These researchers in turn set their research agendas based partly on this local input. In this way, problems like scale discordance are minimized as higher scale researchers can incorporate local concerns and data into larger scale assessment efforts. Given their role as communicators across scales, county agents are accountable to both clients at the local level, and scientists at the state and federal levels.

² Such boundary organizations include the Pacific ENSO Application Center (between climate scientists studying global phenomena and policy-makers/managers on islands throughout the Pacific region), the Cooperative State Research, Education, and Extension Service (CSREES) organized under the US Department of Agriculture (USDA) (between federal, state, and locally situated scientists, and between scientists and farmers), the IPCC (between national diplomatic delegations and climate scientists studying global- and regional-scale climate); the Consultative Group of International Agricultural Research (between international researchers, national researchers, and national and local planners, policy-makers, and farmers); the International Institute for Applied Systems Analysis in its work for the Long-Range Transboundary Air Pollution convention; and the extension service of US Sea Grant colleges (between scientists, coastal management agencies and private resource managers.)

³ Individual states have wide latitude in how the extension system is structured from the state to the local level. County extension agents, for example, are also called extension educators in some states, but the difference in function is minimal. The degree to which these agents (or educators) are affiliated with the agricultural college, or included as faculty, or have tenure-track positions, also varies from state to state.

⁴ In the US, agricultural colleges are more formerly known as “Land-Grant” colleges or universities, names derived from legislation in the 1860s which granted federal land to the states for the purpose of establishing agricultural colleges.

(3) *Insulation from pressures emanating from across the boundary*: Scientists within the CSREES generally have faculty appointments at state agricultural colleges. As faculty members, they maintain academic standards and autonomy and are subject to similar norms (peer review, tenure, etc.) which maintain their credibility in the scientific arena and also insulate them from political intrusion.

(4) *Neutral fora for discussion*: The research and extension system provides a wide range of fora, e.g., seminars, conferences, and informal publications, in which ideas, research findings, and implications for application can be shared and vigorously debated.

(5) *Long-term trust building*: While the CSREES has evolved over its 125 yr existence, the multiple institutionalized avenues of communication and feedback, and the multiple and shared sources of funding (from county, state, and federal levels) have produced a system which has engendered mutual respect and trust between farmers, county agents, researchers, and administrators across all scales (Cash, 1998). Well-established boundary organizations like the CSREES with their trusted, well-connected experts could be instrumental building blocks of an assessment process which aims to effectively and usefully mediate between the needs of information users and decision-makers and the community of scientific experts.

3.2. Utilize scale-dependent comparative advantages

A second critical design choice addresses the need for greater institutionalized cross-scale coordination to further address scale discordance, mismatch and cross-scale dynamics. While calls to do so are not novel, *how* to achieve such coordination is a more challenging and engaging question. One specific way to do so is to harness scale-dependent comparative advantages. Such comparative advantages can be thought of as unique knowledge, technical capacity, or functional specialization characteristic of a specific scale.

With increasing efforts to understand local implications of global phenomena and to explore options for adaptation to environmental change, it has become increasingly important that unique and local knowledge be brought to bear on assessment (Dickson, 1999; Wilbanks and Kates, 1999). This is evident, for example, in the local and regional input solicited in the current US National Assessment of Climate Variability and Change (US Global Change Research Program, 1999).

3.2.1. Technical capacity

Scale-dependent technical capacity refers to the differing abilities of organizations at different levels to undertake various scientific and technical functions such as data collection, monitoring, modeling exercises, and analysis (Blomquist, 1992; Lins et al., 1997). For example, for water management in the US Great Plains, a federal

agency such as the US Geologic Survey is particularly well suited to conduct large-scale (multi-state) hydrologic modeling of surface and groundwater interactions — its “jurisdiction” crosses state boundaries so it can cover the full extent of large aquifers or rivers which cross state lines. Furthermore, as a large federal agency, it has the financial, computing, and human resources to undertake complex modeling exercises. Any one state does not have these capacities, but might have the capacity to store and systematize water data within its boundaries. Finally, local water districts have the unique ability to engage individual landowners in collecting data on numerous characteristics of the resource at local well-monitoring sites, thus contributing to a state-wide database. Each level is dependent on the unique capabilities of data collection, analysis, and interpretation at other levels in order to construct a model that both accurately captures large-scale system dynamics, and can also be “ground-truthed”, while being relevant for different purposes at different levels.

3.2.2. Functional specialization

Decision and policy functions also vary with scale and may best be harnessed by having different functions performed at different levels. For example, the recent move toward devolution of some environmental regulation and resource management authority to state and local levels reflects both a desire to take greater local control of resource management, and to better tailor policy choices to local conditions (Donahue, 1997). Activities such as research funding, enforcement, education, monitoring, and evaluation may be undertaken better at different levels, and hence require that authority, responsibility, and resources be allocated accordingly. Thus we believe that the design choice is not simply one between a centralized or decentralized (top-down vs. bottom-up) assessment and management system, but rather one that integrates the unique capacities and complementarities at the “top”, the “bottom”, and the “middle”.

3.2.3. Enabling policies

Allocating assessment and management responsibilities to various scales is most effective when complemented by “enabling” policies which are constructed at a higher level of governance (e.g., the international or national level). They provide opportunities for, or at least remove constraints on, local decision-making (Ostrom, 1990; Blomquist, 1992; Ostrom et al., 1994). The US Coastal Zone Management Program, for example, establishes broad national management goals and provides states with funds to develop policies and institutions to implement them. Since 1990, with the introduction of the Sec. 309 Enhancement Program (an assessment and improvement program), states are given additional incentives to strengthen their programs, policies and regulations, yet federal incentives are tied to performance

which has pushed many states to streamline and improve their state and local implementation systems (Bernd-Cohen, 1995).

Profiting from such scale-dependent comparative advantages requires not only identifying particular advantages, but understanding how they relate to and complement capacities at other scales. This is analogous to long-held notions of utilizing economies of scale, specialization, and division of labor which are well developed in the fields of economics, industrial organization (Chandler, 1990) and public management (Sparrow, 1994).

Using scale-dependent comparative advantages addresses the challenges outlined earlier in a number of ways. Scale discordance problems are likely to be diminished when parallel and integrated efforts of assessing the problem are undertaken at multiple scales. It also increases the probability that outputs will be better tailored to the needs of decision-makers at different scales as those needs are more directly addressed and matched by technical and institutional strengths elsewhere. Problems matching natural systems to management systems are reduced by gaining a more synoptic understanding of the system at all scales and by allowing for multiple ways to view the problem, connecting these problem framings from different scales, and identifying which management schemes best match the environmental system. By utilizing these advantages, assessors and decision-makers will heighten the scientific credibility, reliability, political salience, and practical usefulness of the assessment to actors at different scales, not in the least because they have been part of and hence familiar with the assessment process.

3.3. *Establish adaptive processes*

Finally, designing an effective integrated assessment and management system for long-term, multi-scale environmental problems is not likely to be a one-time enterprise. Important choices thus must be made regarding how to create a robust yet flexible process. Over the last two decades, theories and practice of adaptive management have evolved as a potentially powerful framework for the dynamic linkage between science and policy. The central notion of this perspective is that for environmental risks characterized by long time horizons and high levels of uncertainty and stochasticity, effective policy should be based on adaptive, iterative, and flexible experimentation. Most characteristically, adaptive assessment and management is a form of explicit learning-oriented policy experimentation to test effective management strategies (Holling, 1978, 1995; Walters, 1986; Lee, 1993; Gunderson et al., 1995). Such approaches provide fora for multi-stakeholder involvement, and, most important for the purposes of this paper, build on theories that usefully conceptualize how natural and human systems

interact across different temporal and spatial scales (Gunderson et al., 1995; Folke et al., 1998; Peterson, 2000). Building flexibility into the linked processes of assessment and management creates the ability to accommodate and address both endogenous and exogenous technical, political and environmental changes.

This approach appears particularly promising in the context of multi-scale problems in which perspectives, interests, capacities, and expertise shift as one moves from one scale to another and through time. For example, serious concern about climate change has only recently begun to emerge at the local scale, so to be most effective, assessment and management systems must be flexible enough to adapt to such changing loci of concerns and interests. Notions of adaptive management suggest that as our understanding of local impacts and adaptation processes grows, assessors and decision-makers, (1) would benefit from incorporating emerging knowledge from different scales, (2) could build on established and trusted communication and interaction channels to reach the most knowledgeable scientists and pertinent decision-makers at different scales, and (3) could receive and incorporate feedback from scientists and decision-makers to respond to the outcomes of management experimentation and thus increase the effectiveness of policies and actions.

While the tenets of adaptive management have been embraced by resource managers, planners, and scientists in many regions and for a variety of management problems, actual implementation of adaptive management regimes has been limited, and has exhibited varying success. The LRTAP convention and the Montreal Protocol are considered two successful examples of institutional structures which consciously accommodated changing scientific and technical information acquired through iterative monitoring, evaluation, and adjustment (Levy, 1994; Parson, 1994; Tuinstra et al., 1999). More limited success has been achieved in the management of salmon fisheries in the Columbia River Basin in the US and Canada (Lee, 1993; National Research Council, 1996b), in the management of the Chesapeake Bay estuarine system (Healey and Hennessey, 1994), and in the Great Lakes ecosystem (Francis and Reiger, 1995).

Two of the major obstacles to more robust implementation are a lack of long-term institutional stability (resulting from shifting federal and state priorities), and an organizational culture characterized by a history of mistrust and conflict that is unable or unwilling to accommodate the risks inherent in experimentation (Lee, 1993; National Research Council, 1996b). Indeed, these obstacles are consistent with empirical analyses of a range of adaptive management efforts which identify at least three critical barriers to the implementation of adaptive management: high costs and risks; threats to existing power structures and interests; and fundamental

differences in how environmental resources are valued (Crance and Draper, 1996; McLain et al., 1996; Walters, 1997).

4. Conclusions

“Global” environmental change is increasingly understood to have implications for assessment and management schemes which span multiple scales, from the local to the global. This multi-scale nature of global environmental problems poses fundamental challenges to how both assessors and managers conduct their work, and more important, interact. These challenges include matching scales of biogeophysical systems with scales of management systems, avoiding scale discordance (matching the scale of the assessment with the scale of management), and accounting for cross-scale dynamics.

In this paper we argue that more traditional models of how science is supposed to inform environmental decision-making, such as the pipeline model, not only are ill-equipped to address these fundamental challenges, but in fact, can exacerbate them. Conceptualizing environmental problems through the lens of scale provides an alternative perspective in assessment and management. The model of boundary organizations, for example, suggests a more nuanced relationship between scientists and decision-makers, and proposes mechanisms that account for two-way interactions between science and decision-making and across scales.

Using these alternative frameworks we have proposed tentative guidelines for meeting the challenges that both assessors and decision-makers face when making design choices in establishing assessment and management systems: (1) to utilize boundary organizations — institutions which serve to mediate between scientists and decision-makers, and between these actors at different scales; (2) to utilize scale-dependent comparative advantages — coordinating the allocation of resources, technical expertise, and decision-making authority to best capitalize on scale-specific capabilities; and (3) to employ adaptive assessment and management strategies — constructing long-term, iterative, experiment-based processes of integrated assessment and management. While these three strategies do not address all assessment design challenges, they can help address the scale-related challenges outlined in this paper. Our empirical research has shown that they help to increase the credibility of participants across scales, and simultaneously better assure the saliency of assessment products for assessment users. Moreover, these three strategies interact synergistically. For example, enduring boundary organizations facilitate adaptive approaches and can help effectively identify and utilize scale-dependent comparative advantages.

The provisional nature of these guidelines and the relative novelty of framing “global” environmental change as a cross-scale problem suggest the importance of further research and analysis. With numerous cases now of assessment and management systems which have explicitly addressed cross-scale dynamics, there is a large empirical base on which to draw that would significantly advance the analysis and theory of cross-scale assessment and management, including emerging models of boundary work and boundary organizations. Such research could probe questions such as: How do different institutional forms of boundary organizations influence incentives that face scientists and decision-makers at different levels? What mechanisms can maintain scientific credibility *and* assure practical relevance? What are the attributes of specific types of environmental and natural resource problems which make them more or less amenable to cross-scale analysis and management? What types of stakeholder participation (roles, degree of authority, input, etc.) are appropriate in a model of cross-scale assessment and decision-making? How can authority and responsibility for both information production and decision-making be delegated across scales in the context of differing notions of equity, democracy, and expertise?

What we learn from such analytical and theoretical advances could usefully inform the design decisions that many international, national, and sub-national institutions face, now and for future assessments, and help avoid some of the more damaging pitfalls of ineffective assessment activities.

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