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The neglected heart of science policy: reconciling supply of and demand for science

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ABSTRACT

The funding of scientific research is almost always justified in terms of the potential for achieving beneficial societal outcomes. In pursuing a particular societal outcome, how can we know if one research portfolio is better than another? In this paper we conceptualize: (1) science in terms of a "supply" of knowledge and information, (2) societal outcomes in terms of a "demand" function that seeks to apply knowledge and information to achieve specific societal goals, and (3) science policy decision-making as a process aimed at "reconciling" the dynamic relationship between "supply" and "demand." The core of our argument is that "better" science portfolios (that is, portfolios viewed as more likely to advance desired societal outcomes, however defined) would be achieved if science policy decisions reflected knowledge about the supply of science, the demand for science, and the relationship between the two. We provide a general method for pursuing such knowledge, using the specific example of climate change science to illustrate how research on science policy could be organized to support improved decisions about the organization of science itself.

1. Introduction to the problem

Most scientific research, whether funded by public or private moneys, is intended to support, advance, or achieve a goal that is extrinsic to science itself. While some research is not expected by anyone to have a result other than the advance of scientific knowledge, such work is an extremely small portion of the overall science portfolio. Funding for research generally considered to be "basic" by those who perform it is usually justified by the expectation that the results will contribute to a particular desired outcome. For example, much of the research supported by the U.S. National Institutes of Health (NIH) is considered "basic" by medical researchers, in that it explores fundamental phenomena of human biology, but robust public support for NIH is explicitly tied to the expectation (and legislative mandate) that research results should end up improving human health.

In pursuing a particular societal goal or set of goals, how do we know if a given research portfolio is more potentially effective than another portfolio? This question would seem to lie at the heart of science policy, yet it is almost never asked, much less studied systematically. Given the complexity of the science enterprise, of the processes of resource allocation, knowledge creation, and knowledge application, it would be very surprising indeed if the capacity of the existing enterprise to advance desired outcomes could not be significantly improved upon. For example, it is broadly accepted that current global priorities in biomedical research are very poorly aligned with global health priorities, a problem commonly termed the "10/90 problem," in reference to the observation that only about 10 percent of the global biomedical research

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budget is allocated to diseases accounting for about 90 percent of the worlds' health problems (Global Forum for Health Research, 1999).

Moreover, doing research always begs the question: "what research?" Looking again at biomedicine, scientists and other science policy decision makers heatedly debate the question of how much emphasis should be placed on exploring the molecular genetic origins of disease, versus environmental, behavior, nutritional, cultural, and other origins (Curtis, 2000; Hoffman, 2000)(e.g., compare Curtis, 2000 with Hoffman, 2000). Similar tensions flare up in debates over the appropriate balance between treatment (e.g., drugs) and prevention (e.g., vaccinations). Genetics and treatment often win out, not necessarily because they are known to be the best routes to advancing human health, but because they lie at the confluence of advanced technology, high prestige science, market incentives, and even ideology (e.g., genetic determinism; Lewontin, 1993).

Indeed, just "doing research" on a problem of societal importance says nothing directly about whether or under what conditions the research can effectively contribute to addressing that problem (Bozeman and Sarewitz, 2005; Sarewitz et al., 2004). A major commitment to AIDS research starting in the late 1980s led in fairly short time to antiretroviral drugs that are, thus far, quite effective in the treatment of AIDS patients. Yet 90 percent of AIDS sufferers have no reasonable prospect of ever receiving this treatment, largely because they (or the societies in which they live) cannot afford it. The potential for science to contribute to societal goals depends critically on factors well beyond science.

Given how little attention is paid to understanding the relationship between alternative possible research portfolios and stipulated societal outcomes, there is no a priori reason to expect that existing research portfolios are more effective than other possible research portfolios at contributing to the achievement of desired societal outcomes. This being the case, the key question – the neglected heart of science policy – is how one might approach the problem of rigorously assessing the relationship between a research portfolio (or a set of alternative portfolios) and the societal outcomes that the portfolio is supposed to advance.

Some would argue that this problem is inherently intractable. Because the connections between research and societal outcomes cannot be accurately predicted in detail, the argument would go, predicting the differing outcomes of an array of hypothetical or counterfactual research portfolios is impossible. We think such arguments (which are common in science policy debates) are wrong-headed and wrong. Wrong-headed because science policy decisions are constantly being justified on the basis of putative linkages between research investments and desired outcomes. If such justifications cannot be supported analytically or logically, then they should not be asserted in the first place. Wrong because contingency, complexity and non-linearity (i.e., in the relations between science policy decisions and societal outcomes) are obstacles to accurate predictions, but they need not prevent improved decision-making (e.g., Lasswell, 1971; Lindblom, 1959; Sarewitz et al., 2000), where "improved" means more likely to achieve desired outcomes.

Our approach in this paper is to conceptualize science in terms of a "supply" of knowledge and information, societal outcomes in terms of a "demand" function that seeks to apply knowledge and information to achieve specific societal goals, and the relationship between the two as "reconciled," in part, through science policy decision processes. In the next section we develop this conceptualization, drawing briefly from many areas of science policy scholarship. The core of our argument is that "better" science portfolios (that is, portfolios plausibly viewed as more likely to advance desired societal outcomes, however defined) would be achieved if they reflected an understanding of the supply of science, the demand for science, and the complex, dynamic relationship between the two. We will provide a general method for pursuing such knowledge, using the specific example of climate change science to illustrate how research on science policy could be organized to support improved decisions about the organization of science itself.

2. Understanding and mediating the supply of and demand for science in science policy

We borrow from economics the concepts of "supply" and "demand" to discuss the relationship of scientific results and their use for several reasons (cf., Broad, 2002; Dalrymple, 2006). First, the analogy is straightforward. Decisions about science (i.e., science policy decisions) determine the composition and size of research portfolios that "supply" scientific results. People in various institutional and social settings who look to scientific information as an input to their decisions constitute a "demand" function for scientific results. Of course, the demand function can be complicated by many factors, e.g., sometimes a decision maker may not be aware of the existence of useful information or may misuse, or be prevented from using, potentially useful information. In other cases, necessary useful information may not exist or may not be accessible. But our key point is that there is reasonable conceptual clarity in distinguishing between people, institutions, and processes concerned with the supply of science, and those concerned with its use. Indeed, conventional notions of science policy exclusively embody decisions related to the former.

Nonetheless, a second reason for characterizing scientific research in terms of supply and demand is to recognize that, just as in economics, in the case of science supply and demand are closely interrelated. Science policy decisions are not made in a vacuum but with some consideration or promise of societal needs and priorities. Thus there is a feedback between the (perceived) demand for science and the (perceived) characteristics of supply. People with spinal cord injuries or diabetes, influenced by the rhetoric of scientists studying embryonic stem cells, in turn create an enhanced demand for such research. However, whether embryonic stem cell research is itself the "right" path to achieving the desired goals (in this case, presumably cures for the injuries or diseases) is not necessarily apparent. Numerous alternative paths may be available (Garfinkel et al., 2006).

At the same time, we recognize the power and importance of scholarship over the past several decades that reveals the complex manner in which science and society co-evolve, or are co-produced (e.g., Jasanoff, 2004). The insights from such work dictate that categories such as "supply" and "demand" cannot be understood as conceptually discrete or fully coherent. Moreover, both supply of and demand for information emerge from complex networks of individuals and institutions with diverse incentives, capabilities, roles, and cultures. Yet in the face of such complexity, decisions about resource allocation, institutional design, program organization, and information dissemination have been and are still being made. That is, while notions of "supply" and "demand" may embody considerable complexity, they also represent something real and recognizable: on the one hand, people conducting research that has been justified in terms of particular societal outcomes, and on the other, people making decisions aimed at contributing to those outcomes.

Some think the supply function is inherently optimized so long as scientists are freely pursuing knowledge with minimal external interference. This position, most rigorously espoused by Polanyi (1962), views the scientific community as an autonomous, self-regulating market organized to identify and pursue the most efficient lines of knowledge generation. Any "attempt at guiding scientific research toward a purpose other than its own is an attempt to deflect it from the advancement of science" (1962, p. 62). From this perspective, the supply of scientific knowledge is best generated without any connection or attention to demand for particular types of knowledge.

The apparent logical and practical weakness of this perspective – that knowledge, efficiently pursued, may or may not be knowledge that has any utility in the world – has been answered in two ways. First, basic knowledge is conceived as accumulating in a metaphorical reservoir from which society can draw to solve its multifarious problems. The reservoir is filled most rapidly and effectively through the advance of science independent of considerations of application. Second, application of basic knowledge to real world problems is often serendipitous, so there is no way to predict the connection between a given line of research and a given social goal. Chemistry (or, one supposes, solid earth geophysics or cosmology) is as likely to help cure a certain disease as is molecular genetics. Numerous anecdotes are offered up to illustrate the significance of serendipity in connecting inquiry to utility (Sarewitz, 1996).

Of course no one really advocates this model in its extreme form. Certainly, if the time scale is long enough (decades and beyond), fundamental advances in knowledge often have broad application beyond anything that could be anticipated, but on the time scales that motivate support for research, strategic investments in basic understanding are invariably conceived in the context of related areas of potential application. This reality has given rise to a weaker version of the science-as-a-self-regulating-market argument, where the need to make strategic investment choices among disciplines and research topics is tacitly acknowledged, but scientists and science advocates still argue that they are best positioned to contribute to social goals if they are given autonomy to pursue knowledge in directions guided by the logic of nature, not the exigencies of social need (Committee on Science Engineering and Public Policy, 1993; Pielke and Byerly, 1998).

The idea that the creation of scientific knowledge is a process largely independent from the application of that knowledge within society has had enormous political value for scientists, because it allows them to make the dual claims that (1) fundamental research divorced from any consideration of application is the most important type of research (Weinberg, 1971) and (2) such research can best contribute to society if it is insulated from such practical considerations, thus ensuring that scientists not only have putative freedom of inquiry, but also that they have control over public resources devoted to science. The continued influence of this perspective was recently asserted by Leshner (2005), Chief Executive Office of the American Association for the Advancement of Science: ". . . historically science and technology have changed society, society now is likely to want to change science and technology, or at least to help shape their course. For many scientists, any such overlay of values on the conduct of science is anathema to our core principles and our historic success."

Empirical studies of the complex connections between research and societal application give little support to the foregoing conceptions. One of the richest areas of scholarship in this realm has focused on the origins of technological innovation, where case studies and longitudinal surveys have revealed networks of continual feedbacks among a large variety of actors, including academic scientists, industrial scientists, research administrators, corporate executives, policy makers, and consumers. The resulting picture is complex and yields no single, straightforward model for how knowledge and application interact; yet one feature that invariably characterizes successful innovation is ongoing communication between the producers and users of knowledge. Moreover, historical studies of innovation typically show precisely the opposite of what one would expect from the autonomous science argument. Emerging technological frontiers often precede deep knowledge of the underlying fundamental science. It is precisely the demand for better theoretical foundations among those worried about applications that has driven the growth of fundamental science in many areas (e.g., Rosenberg, 1994). As economist Nelson (2004) writes: "for the most part science is valuable as an input to technological change these days because much of scientific research is in fields that are oriented to providing knowledge that is of use in particular areas."

If this seems spectacularly circular, then that is precisely the point: science agendas are closely aligned with areas of technological application because certain areas of science demonstrate themselves to be of particular value to some groups of users. This is a very different view of the world than one in which science advances independently of subsequent applications. Research on the relations between industry and universities, for example, strongly demonstrates that the priorities of academic basic science have long been aligned with the needs of industry (e.g., Crow and Tucker, 2001; Mowery and Rosenberg, 1989). Such alignment is not a result of serendipity, but of the development of networks that allow close and ongoing communication among the multiple sectors involved in technological innovation. Thus, fundamental research relevant to innovation does indeed go on in universities where scientists have considerable autonomy to pursue basic knowledge, but the priorities and directions of this fundamental work are strongly influenced by collaboration with scientists, engineers, and managers working closer to the actual point of product development and application (and they, in turn, are influenced by a variety of end-users or consumers). In the useful term introduced by Stokes (1997), this type of fundamental science is ''use-inspired,'' and it is central to the successful functioning of modern, high technology economies. More generally, the production of knowledge in the broader context of applications has been termed Mode 2 science by Gibbons et al. (1994), to distinguish it from the traditional insistence on ''pure'' science as the ultimate source of social value.

Two attributes of this discussion bear emphasis. The first is that, in contrast to the canonical portrayal of fundamental science contributing to application because it is free to advance in isolation from consideration of application, studies of technological innovation have often shown exactly the opposite—that it is the awareness of potential application and utility that ensure the contribution of fundamental research to innovation. Second, in contrast to the portrayal of scientific advance as something that is unpredictable and therefore beyond planning or control through influences beyond the scientific enterprise, the history of post-World War II science and technology policy is one of strategic decisions about investments in particular areas of science and engineering in support of specific areas of societal application, such as communications, computing, advanced materials, aviation and avionics, weapons systems, and biotechnology. From the creation of agricultural research stations in the mid 19th century, to the advent of the transistor shortly after World War II, to the continued advance of human biotechnologies today, strategic decisions to focus public sector resources in particular areas of science have consciously and successfully linked research portfolios to technological advance and such societal outcomes as economic growth, agricultural productivity, and military power.

Such outcomes are themselves highly complex, of course. In the past several decades, other lines of scholarship (e.g., Jasanoff et al., 2001) have illuminated how the multifarious societal consequences of scientific and technological advance bear clear evidence of a dynamic relationship between the producers and users of knowledge and innovation, and that this relationship itself is strongly conditioned by broader contextual factors.

For example, the natural, cultural, and political attributes of the United States in the 19th century gave rise to an organization of agricultural science closely tied to the practice of farming and the needs of farmers (and strongly resisted, at first, by scientists seeking to preserve their autonomy), including the development of institutional innovations – the agricultural research station and extension services – to bring supply and demand sides together (e.g. Cash, 2001; Rosenberg, 1997). The inextricable linkages between science, technology, and the geopolitics of the Cold War drove the institutional symbiosis of universities, corporations, and the military that dominated the demand–supply relation in U.S. science for half a century and motivated President Eisenhower's (1960) famous warning about the overweening power of the ''military-industrial complex.'' Feminism and the growing political power of the women's movement in the U.S. eventually led to an understanding that a health research system run by males was often biased toward males in its priorities, practices, and results. Such insights, which were at the time controversial but are now widely accepted, led to significant changes both in the conduct of science and its application in ways that benefit women (e.g., Lerner, 2001; Morgen, 2002). Similarly, the political empowerment arising from the gay rights movement in the U.S. ultimately influenced the course of AIDS research in ways that directly benefited AIDS sufferers in the U.S., for example through more rapid clinical testing and approval of treatments (Epstein, 1996). Based on these successes, ''disease lobbies'' in the U.S. have become a significant factor in shaping biomedical research priorities.

Such examples illustrate that the supply of science is often responsive to the presence of a well-articulated demand function. Put somewhat more bluntly, scientific research trajectories are often decisively influenced through the application of political pressure by groups with a stake in the outcomes of research and the power and resources necessary to make their voices heard. Obviously, this does not mean that science can produce whatever is asked of it. Moreover, groups lobbying for one type of research or another may or may not actually understand how best to advance their interests. For example, it might be the case that health care delivery reform or changes in behavior would return greater benefits to some disease lobbies than more funding for a particular type of research.

More significantly, there is no reason to think that the influence of particular political interest groups (whether they be disease lobbies or pharmaceutical corporations) on the supply of science will yield outcomes that are broadly beneficial to society; they may, on the contrary, lead to the preferential capture of benefits by certain groups (Bozeman and Sarewitz, 2005). For instance, the very fact that most health research is carried out in affluent societies and responds to the health needs of affluent people has resulted in an increasingly wide gap between science agendas and global health priorities. Scientific opportunities that are likely to yield the greatest return in terms of social benefit (e.g., through vaccine development) are widely neglected. Nonetheless, politics provides a key mechanism for mediating the relationship between – for reconciling – supply of and demand for science via the science policy decision processes that so strongly determine the character of the supply function.

The philosopher Kitcher (2001) has identified an ideal, which he terms ''well-ordered science,'' that describes an optimal relationship between supply and demand (though he does not articulate it using these terms), achieved through an ideal process of representative deliberation:

> For perfectly well-ordered science we require that there be institutions governing the practice of inquiry within society that invariably lead to investigations that coincide in three respects with the judgments of ideal deliberators, representatives of the distribution of [relevant] viewpoints within society. First, at the stage of agenda-setting, the assignment of resources to projects is exactly the one that would be chosen through the process of ideal deliberation... Second, in the pursuit of the investigations, the

strategies adopted are those which are maximally efficient among the set that accords with the moral constraints the ideal deliberators would collectively choose. Third, in the translation of results of inquiry into applications, the policy followed is just the one that would be recommended by ideal deliberators. . .'' (2001, pp. 122–123).

Well-ordered science, like all ideals (democracy, justice, freedom), sets a standard that cannot be met but toward which aspirations can be aimed: science that is maximally responsive to the needs and values of those who may have a stake in the outcomes of the research; the best possible reconciliation of supply and demand. This philosophical ideal adds a normative overlay to what has been demonstrated empirically. Not only are the supply of and demand for science related to each other through a process of politically mediated feedbacks, but in a democracy it is desirable that this feedback process be maximally responsive to the negotiated common interests of relevant stakeholders, rather than captured by particular special interests. Indeed, as Kitcher (2003, p. 218) asserts: ''the current neglect of the interests of a vast number of people represents a severe departure from well-ordered science.''

Kitcher's notion of ''well-ordered science'' is procedural; it describes a well-informed process of defining research agendas and practices that reflects the priorities and norms of relevant stakeholders (including, of course, scientists involved in the research). In the real world, intermediary institutions – sometimes called boundary organizations – may enhance the pursuit of well-ordered science by mediating communication between supply and demand functions for particular areas of societal concern (see McNie, this issue, for a comprehensive review). Again, this is not a matter of asking scientists to ''cure cancer'' or ''end war,'' it is a process of reconciling the capabilities and aspirations of knowledge producers and knowledge users.

Even if the procedural ideal were achieved, it would not guarantee the achievement of a particular stipulated social outcome. Many of the goals of science – curing a given disease, for example – may be difficult to attain for a variety of reasons, ranging from intrinsic scientific difficulty to cultural or institutional complexities. But the key point is that departures from well-ordered science are inherently *less* likely to achieve such outcomes, because research agendas will not reflect the priorities, needs and capabilities of the broadest group of constituents that could potentially make use of the resulting knowledge and innovation.

3. Supply of and demand for science in decision-making

Our discussion so far has aimed at building a conceptual foundation for assessing the relations between supply of and demand for science as input to the science policy decisions that help reconcile those relations. We have shown: (1) that the notion of supply and demand functions for science helps to clarify the dynamic role of science in society; (2) that supply of and demand for science are reconciled in various ways, with various degrees of success (depending in part on who defines ''success''); (3) an ideal reconciliation of supply and demand would match the capabilities of science with the needs of those who could most benefit from it. We now apply these insights to what logically ought to be the most obvious – and tractable – problem of supply–demand relations in science: the use of science to support decision-making in public affairs.

In areas as diverse as national innovation strategies, technological risk, and environmental protection, science is increasingly called upon to provide information that can improve decision-making in public affairs (House Committee on Science, 1998; UNDP, 2001). This growing role for science in part reflects the increasing capacity of scientific methods and tools to study complex systems ranging from genes to climate. But it also reflects the rapidity of societal evolution that results from the increasing power and global reach of science and technology. That is, science is called upon as a tool to monitor and assess the changes that science itself helps to induce (see Beck, 1992). The expectation that science can help inform human decisions about societal change has been especially strong in the area of the environment, and we focus our discussion on the problem of climate change.

Research on decision-making has long recognized that there is no simple connection between ''more information'' and ''better decisions'' (Clark and Majone, 1985; Feldman and March, 1981; Sarewitz et al., 2000), and that, to the extent ''more information'' does not solve a problem, the fault cannot simply be located with the decision maker (i.e., in the demand function). More information may not lead to better decisions for many reasons, e.g., the information is not relevant to user needs; it is not appropriate for the decision context; it is not sufficiently reliable or trusted; it conflicts with users' values or interests; it is unavailable at the time it would be useful; it is poorly communicated. Also, of course, the idea of ''better decisions'' depends on who stands to benefit from which decisions. Some types of information may support decisions that benefit some people but adversely affect others.

Apparently commonsensical ideas, for example, that climate forecasts would be valuable to people who make decisions related to climate behavior (e.g., water managers, emergency managers, agricultural planners) turn out to be very complex, as such factors as institutional structures, prior practice, socioeconomic conditions, and political stakes and power distributions, strongly influence the types of information that decision makers need and use, and the array of stakeholders that might benefit from such decisions (e.g., Broad, 2002; Lahsen, in press; Lemos et al., 2002; NRC, 1999; Rayner et al., 2002).

Scholars striving to understand the behavior of scientific information in complex decision contexts (especially those related to the environment and sustainability) have converged on the recognition that the utility of information depends on the dynamics of the decision context and its broader social setting (e.g., Jasanoff and Wynne, 1998; Pielke et al., 2000). Utility is not immanent in the knowledge itself. For example, Gibbons (1999) describes the transition from a gold standard of ''reliable'' knowledge as determined by scientists themselves, to ''socially robust'' knowledge that, first, ''is valid not only inside but also outside the laboratory. Second, this validity is achieved through involving an extended group of experts, including lay 'experts'. And third, because 'society' has participated in its genesis, such knowledge is less likely to be contested than that which is merely reliable'' (1999, p. C82).

Arriving at a similar set of insights, Cash et al. (2003) have shown that information capable of improving decisions about the management of complex environmental systems must have the three attributes of credibility, salience, and legitimacy, attributes which can only emerge from close and continual interactions among knowledge producers and users. Pielke et al. (2000) similarly recognized that effective integration of science and decision-making required a tight coupling among research, communication, and use. Guston (1999) pointed to the value of boundary organizations at the interface between science and decision-making for helping to ensure that such integration can occur. Funtowicz and Ravetz (1992) coined the term ''post-normal science'' to describe the complex organization of knowledge production necessary to address problems of decision-making, in contrast to older notions of autonomous – ''normal'' – scientific practice.

Despite these conceptual advances – derived, in part, from studying relative successes in such areas as international agricultural research and weather forecasting – the overall picture is neither clear nor encouraging. While the rich world spends billions annually on research aimed at supporting environmental policy, there is not much evidence that significantly enhanced decision-making capabilities or environmental outcomes have resulted (Cash et al., 2003; Lee, 1999; Millennium Ecosystem Assessment, 2005; Sarewitz, 2004). To suggest that ''politics'' has prevented progress on such issues is merely to restate the problem. Indeed, the recent spate of media and public attention focused on the problem of the ''politicization of science'' in the U.S. (e.g., Gough, 2003; Mooney, 2005; UCS, 2004) reflects the persistent notion that the contribution of science to decisions is mostly a process of delivering facts to users, and that failure to attend to facts reflects problems in the demand function (i.e., ''politics''). This debate is oblivious to the sorts of insights summarized above, which teach us that science is always politicized, and that the real-world challenge is to cultivate an inclusive and non-pathological process of politicization (Pielke, in press; Sarewitz, 2004) that allows a democratically appropriate – well-ordered – reconciliation of supply of and demand for information or knowledge. Put somewhat differently, understanding the politics embodied in the supply and demand functions is a key analytical task in support of their improved reconciliation via science policy decisions.

While there are many complex reasons why it is difficult to generate ''socially robust knowledge,'' scholarly attention has focused principally on the dynamics of interactions between knowledge producers and decision makers, and on the need for institutional innovation to enhance such interactions, as briefly summarized above. Very little consideration has been given, however, to science policy—that is, to the decision processes that strongly determine the priorities, institutional settings, and metrics of success for the supply of scientific research (Bozeman and Sarewitz, 2005; Marburger, 2005). Correspondingly, very little consideration has been given to the types of information or knowledge that science policy decision makers could call upon to improve the reconciliation of supply and demand.

The neglect of science policy is especially problematic because the science policy decisions that strongly determine research portfolios, particularly at the macro level, are likely to be made by people, and in institutions, that are distant from the interfaces between research and its potential use. Indeed, the complex interactions among knowledge producers, knowledge users, and intermediaries that characterize post-normal science often takes place within a context of scientific research agendas whose main characteristics have already been determined through science policy decisions. To further complicate matters, the very process of establishing such characteristics helps to empower some potential users (who may benefit from the structure of the supply function) while marginalizing others. These problems are particularly acute for large scale, long-term research efforts, such as global climate change science.

4. Origins of the climate change supply function

In 2003, seven leading U.S. climate scientists wrote (in response to an article by the authors of this paper (Pielke and Sarewitz, 2003)):

> The basic driver in climate science, as in other areas of scientific research, is the pursuit of knowledge and understanding. Furthermore, the desire of climate scientists to reduce uncertainties does not... arise primarily from the view that such reductions will be of direct benefit to policy makers. Rather, the quantification of uncertainties over time is important because it measures our level of understanding and the progress made in advancing that understanding (Wigley et al., 2003).

This argument restates the traditional logic for public support of science, discussed at the beginning of our paper: that the exploration of nature, motivated by the desire for understanding, is the best route to beneficial social outcomes. It is consistent with (though more extreme than) the original rationale for the U.S. Global Change Research Program (USGCRP), under whose aegis more than $25 billion were spent on climate research between 1989 and 2003. While the USGCRP was intended by policy makers to provide ''useable knowledge'' for decision makers, its structure and internal logic reflected the belief that the best route to such useable knowledge was via research motivated predominantly by a desire to expand fundamental understanding. The USGCRP was also motivated by the belief that decision-making would be improved simply by providing additional scientific information (with a particular focus on predictive models) to those making decisions (Pielke, 1995, 1999).

To the extent that the USGCRP's science priorities were responsive to a particular decision context or demand function, this function was the international assessment and negotiation processes aimed at arriving at a global regime for stabilizing greenhouse gas emissions. To the extent that scientists who conduct climate research, and putative users of that science, were interacting, they were doing so mostly as part of the process of developing this regime. The key point here is that the science agenda (i.e., supply function) was linked to an extremely restricted expectation of what sorts of policies would be necessary to deal with climate change (i.e., global policies that governed greenhouse gas emissions), via simplistic but politically powerful notions about what would cause those policies to come about (i.e., increased scientific knowledge about climate change). In this highly restricted, supply-dominated context, the Intergovernmental Panel on Climate Change (IPCC) issued reports throughout the 1990s and early 2000s, written by teams of scientists that assessed the state of expanding knowledge about climate, while the U.S. National Research Council (NRC) issued reports, written by teams of scientists that analyzed research needs and priorities in the context of pursuing a comprehensive understanding of climate behavior. These expert-driven, supply-focused processes were the controlling political influences on the evolution of the climate research agenda (Agrawala, 1998a, b).

The fact that so many billions have been spent on climate research, not just in the U.S. but in other developed countries as well, in turn suggests that there is a demand function which is being served by this research (otherwise, why would policy makers keep spending the money?), although in fact very little is known about the structure and objectives of that demand function. To the extent that the IPCC can be viewed as a sort of boundary organization aimed at connecting the science to its use in society, then this demand function is mostly embodied in the international process for negotiating and implementing climate treaties under the U.N. Framework Convention on Climate Change, especially the Kyoto Protocol. Politicians and policy makers in the U.S. have, over the years, justified their support of the USGCRP largely in terms of the need to have better information before making decisions about climate, where "decisions about climate" has generally meant decisions about emissions reductions under the Framework Convention.

Yet the problem of climate change implicates a much broader array of potential decision makers in the climate change arena than those with a stake in international negotiations (e.g., see Rayner and Malone, 1998; Sarewitz and Pielke, 2000), and would include farmers and foresters, local emergency managers and city planners, public health officials, utility operators and regulators, and insurance companies, among many others. Such constituencies, which define a diverse demand function, have little impact on the evolving agenda for climate research, which has been driven almost exclusively by scientific organizations such as the IPCC and the NRC. In 2003 an exhaustive strategic planning process aimed at refining the USGCRP was dominated by scientific voices plus civil society groups advocating action on the Kyoto Protocol, with little input from actual decision makers who influence, are influenced by, and must respond to, climate change and climate impacts. The resulting *Strategic Plan for the U.S. Climate Change Science Program* (U.S. Climate Change Science Program, 2003) contains comprehensive recommendations for continuing and expanding climate research, but little information about the needs and capabilities of the potential users of that information (though the report does highlight the importance of such users), and little analysis of how research is actually supposed to benefit various types of users.

Meanwhile, relatively sparse but consistent research conducted under the category of "human dimensions of climate change" (mostly focused on annual to interannual climate variability) has shown that available information on climate is in some cases not deemed useful by decision makers (e.g., Callahan et al., 1999; NRC, 1999; Rayner et al., 2002), in other cases benefits particular users at the expense of others (e.g., Broad, 2002; Lemos et al., 2002), and in yet other cases is misused and contributes to undesired outcomes (e.g., Broad, 2002; Pielke, 1999), and in all cases depends for its value on the types of institutions that are making the decisions (Cash et al., 2003). Overall, however, the institutional structures and feedback processes that lead to increased understanding between supply and demand sectors (characteristic of Mode 2, post-normal, or well-ordered science, and documented as a key element of high technology innovation processes) are largely absent from the climate research enterprise, especially in the United States. *The Potential Consequences of Climate Variability and Change* (National Assessment Synthesis Team, 2001) did encompass a series of regional meetings involving, with various degrees of success, certain stakeholders, but this process has not been institutionalized; rather, it culminated in several reports whose purpose was "to synthesize, evaluate, and report on what we presently know about the potential consequences of climate variability and change for the US in the 21st century." The question of whether "what we presently know" is what we need to know to act effectively was not addressed.

5. Reconciling supply and demand in climate science: a proposed method

The insights derived from several decades of scholarship on the relationship between the production and use of knowledge in many domains of research and application suggest that the organization of climate science in the United States is unlikely to show a strong alignment between the supply of and demands for knowledge among a broad array of potential users. Adopting Kitcher's term, we here hypothesize that climate science is very far from being "well ordered." More importantly, we suggest both that this hypothesis is testable and that, given the scale of public investment and the potential environmental and socioeconomic stakes, the effectiveness of science policies could be greatly enhanced by testing it.

As long ago as 1992, a first (and, as far as we can know, last) step along these lines was taken in the *Joint Climate Project to Address Decision Maker's Uncertainty* (Bernabo, 1992). The project sought to determine "what research can do to assist U.S. decision makers over the coming years and decades," it argued that "[a]n ongoing process of systematic communication between the decision-making and the research communities is essential," and it concluded that "[t]he process started in this project can serve as a foundation and model for the necessary continued efforts to bridge the gap between science and policy" (1992, p. 86).

More than a decade later, the scale of the climate research enterprise, in the U.S. as well as other affluent nations, has increased enormously, along with fundamental understanding of the climate system. At the same time we observe that there is little if any evidence that this growth of understanding can be connected to meaningful progress toward slowing the negative impacts of climate on society and the environment.[1] On the other hand, appreciation of the variety of decision makers and complexity of decision contexts relevant to climate change has greatly deepened. Understanding of this diversity should allow us to ask: what types of knowledge might contribute to decision-making that could improve the societal value of climate science? Next, we outline a methodology of science policy research for assessing and reconciling the supply and demand functions for climate science information.

5.1. *Demand side assessment*

Research on the human dimensions of climate, though modestly funded over the past decade or so, has made important strides in characterizing the diverse users of climate information (be they local fisherman and farmers or national political leaders); the mechanisms for distributing climate information; the impacts of climate information on users and their institutions. This literature provides the necessary foundations for constructing a general classification of user types, capabilities, attributes, and information sources. This classification can then be tested and refined, using standard techniques such as case studies, facilitated workshops, surveys and focus groups. Given the breadth of potentially relevant stakeholders, such a demand side assessment would need to proceed by focusing on particular challenges or sectors, such as carbon cycle management, agriculture, ecosystems management, and hazard mitigation.

5.2. *Supply side assessment*

Perhaps surprisingly, the detailed characteristics of the supply side – the climate science community – are less well understood than those of the demand side. One reason for this of course is that over the past decade or so there has been some programmatic support for research on the users and uses of climate science, but no similar research on climate research itself. Potentially relevant climate science is conducted in diverse settings, including academic departments, autonomous research centers, government laboratories, and private sector laboratories, each of which is characterized by particular cultures, incentives, constraints, opportunities, and funding sources. Understanding the supply function demands a comprehensive picture of these types of institutions in terms that are analogous to knowledge of the demand side, looking at organizational, political, and cultural, as well as technical, capabilities. Such a picture should emerge from analysis of documents describing research activities of relevant organizations, from bibliometric and content analysis of research articles produced by these organizations, and from workshops, focus groups, and interviews. The result would be a taxonomy of suppliers, supply products, and research trajectories. As with the demand side assessment, the scale of the research enterprise suggests that this assessment process should build up a comprehensive picture by focusing sequentially on specific areas of research (such as carbon cycle science). This incremental approach also allows the assessment method to evolve and improve over time.

5.3. *Comparative overlay*

Assessments of supply and demand sides of climate information can then form the basis of a straightforward evaluation of how climate science research opportunities and patterns of information production match up with demand side information needs, capabilities, and patterns of information use. In essence, the goal is to develop a classification, or "map," of the supply side and overlay it on a comparably scaled "map" of the demand side. A key issue in the analysis has to do with expectations and capabilities. Do climate decision makers have reasonable expectations of what the science can deliver, and can they use available or potentially available information? Are scientists generating information that is appropriate to the institutional and policy contexts in which decision makers are acting? Useful classifications of supply and demand functions will pay particular attention to such questions. The results of this exercise should be tested and refined via stakeholder workshops and focus groups.

The 2 × 2 matrix shown in Fig. 1 schematically illustrates the process. We call this the "missed opportunity" matrix because the upper left and lower right quadrants indicate where opportunities to connect science and decision-making have been missed. Areas of positive reinforcement (lower left) indicate effective resource allocation where empowered users are benefiting from relevant science. As discussed above, this

		Demand: Can User Benefit from Research?	
		YES	NO
Supply: Is Relevant Information Produced?	NO	Research agendas may be inappropriate.	Research agendas and user needs poorly matched; users may be disenfranchised.
	YES	Empowered users taking advantage of well-deployed research capabilities.	Unsophisticated or marginalized users, institutional constraints, or other obstacles prevent information use.

Fig. 1 – The missed opportunity matrix for reconciling supply and demand.

[1] This is not the place to flesh out this argument, but see, e.g., Schelling (2002), Pielke and Sarewitz (2003), Rayner (2004), and Victor et al. (2005). While some would regard the coming-into-force of the Kyoto Protocol as evidence of progress in this realm, no responsible scientific voices are claiming that Kyoto will have any discernible effect on negative climate impacts.

situation is most likely to emerge when information users and producers are connected by, and interact through, a variety of feedback mechanisms. Areas of negative interference may indicate both opportunities and inefficiencies. For example, if an assessment of demand reveals that certain classes of users could benefit from a type of information that is currently not available (upper left), then this is an opportunity—if provision of the information is scientifically, technologically, and institutionally feasible. Another possibility (lower right) would be that decision makers are not making use of existing information that could lead to improved decisions, as Callahan et al. (1999) documented for some regional hydrological forecasts. An important subset of the problem represented in this quadrant occurs when the interests of some groups, for political or socioeconomic reasons, are actually undermined because of the ability of other groups to make use of research results, as Lemos et al. (2002) demonstrated in a study of regional climate forecasts in northeast Brazil. Finally (upper right), research might not be relevant to the capabilities and needs of prospective users, as Rayner et al. (2002) demonstrated in their study of water managers.

5.4. *Institutional context*

Decisions emerge within institutional contexts; such contexts, in turn, help to determine what types of information may be useful for decision-making. Supply and demand must ultimately be reconciled within science policy institutions, such as relevant government agencies, legislative committees, executive offices, non-governmental advisory groups, etc. Institutional attributes such as bureaucratic structure, budgeting, reporting requirements, and avenues of public input, combine with less tangible factors including the ideas and norms embedded within an institution, to drive decision-making about the conduct of research and the utility of results (e.g., Keohane et al., 1993; Kingdon, 1984; Laird, 2001; Schön and Rein, 1994; Wildavsky, 1987). How do research managers justify their decisions? Are those justifications consistent with the decisions that they actually make? What ideas or values are implicit in the analyses and patterns of decisions that the institution exhibits? What incentives determine how information is valued? These sorts of questions can be addressed through analysis of internal and public documents, interviews, and public statements about why and how research portfolios are developed. McNie (this issue) provides a more thorough discussion of what is known about how science policy institutions help mediate supply and demand. This remains a key area for additional research, but is largely beyond the scope of our discussion here.

Our analysis of the evolution of the climate science enterprise in the U.S. indicates that policy assumptions and political dynamics have largely kept the supply function insulated from the demand function except in the area of the international climate governance regime (e.g., Pielke, 2000a,b; Pielke and Sarewitz, 2003). Some modest experiments, notably the RISA (regional integrated sciences and assessment) program of the National Oceanographic and Atmospheric Administration, have sought to connect scientists and research agendas to particular user needs at the local level, but these lie outside the mainstream of the climate science enterprise.[2]

A research effort of the type sketched here can illuminate how well climate science supply and demand are aligned and who benefits from existing alignments. It can highlight current successes and failures in climate science policy, identify future opportunities for investment, and reveal institutional avenues for, and obstacles to, moving forward. Consistent with our perspective throughout this paper, the value of the method will in great part depend on how receptive science policy makers are to learning from the results of such research. We fully accept, of course, that knowledge generated about science policy is subject to the same pitfalls of irrelevance, insulation, neglect, mismatch, and misapplication that motivate our investigation in the first place. But our understanding of the current context for science policy decision-making gives us two reasons for optimism. First, the fundamental justification for the public investment in climate science is its value for decision-making. This justification, repeated countless times in countless documents and public statements, thus defines a baseline for assessing accountability and measuring performance via the type of approach we have described here. Second, and of equal importance, the very process of implementing the method we describe will begin to create communication, reflection, and learning among science policy decision makers and various users and potential users of scientific information hitherto unconnected to the science policy arena. In other words, the research method itself creates feedbacks between supply and demand that will expand the constituencies and networks engaged in science policy discourse, expand the decision options available to science policy makers, and thus expand the opportunities to make climate science more well ordered. Undoubtedly, institutional innovation would need to be a part of this process as well, given the scale and scope of the climate science enterprise and the potential user community.

As a first step toward testing both this method (which should, of course, have broad applicability beyond climate change science) and the specific hypothesis that climate change science is far from well ordered, we convened two workshops to consider supply of and demand for science related to the global carbon cycle. Carbon cycle science is a high priority area of focus in climate change science, with annual public expenditures in the U.S. in excess of $200 million. Research priorities have been established largely in the manner described above, with little engagement between supply and demand sides (Dilling, this issue). Nevertheless, the investment in carbon cycle science is justified in terms of its value for a variety of information users in industry, agriculture, government, and other sectors (Dilling et al., 2003).

Our workshops[3] brought together leading carbon cycle researchers, science policy decision makers, and users representing ''carbon cycle management'' decision contexts

[2] More information on how the RISAs seek to reconcile supply and demand of climate information can be found at: http://www.sciencepolicy.colorado.edu/sparc/research/projects/risa/risaworkshop05.html.

[3] For more information, see: http://www.sciencepolicy.colorado.edu/sparc/research/projects/rsd/ccworkshop05.html.

such as urban environmental planning, energy production, agriculture, and emissions trading. Perhaps not surprisingly, most users reported that they benefited little, if at all, from recent advances in carbon cycle science (the single exception being the user engaged in developing emissions trading schemes), and, importantly, that they would greatly welcome specific types of knowledge and information that could enhance their capacity to make effective ‘‘carbon management’’ decisions. The extent to which this poor reconciliation between supply and demand reflected the inability of users to take advantage of relevant available information (lower right quadrant in the matrix above), versus a failure to generate relevant and usable scientific information (upper left and right quadrants), awaits further analysis and a more rigorous implementation of our method (guided by what we learned during the workshop). But the larger point is that this level of reconnaissance supports the hypothesis that the science is not well ordered, as well as the prospect that a better reconciliation of supply and demand is both possible and desirable.

6. Conclusion: enhancing public value in public science

In the public sector, science policy decision-making is mostly about how to allocate marginal increases in funding among existing research programs. At the same time, such allocation decisions are usually justified in terms of their value in pursuing societal outcomes extrinsic to science itself. In a world of limited science resources, then, it would seem more than sensible to bolster such justifications with better understanding of the implications of science policy decisions for societal outcomes. Nevertheless, consideration of how alternative research portfolios might better achieve stipulated societal outcomes is not a regular part of science policy discourse or decision processes.

There are several reasons for this, including:

1. The widespread belief that more science automatically translates into more social benefit;
2. The insulation of science policy decision processes from the contexts within which scientific knowledge is used;
3. The capture of science policy decision process by narrow political constituencies (drawn from either the supply or demand side);
4. The natural resistance of bureaucratic decision processes to changes inside the margins;
5. The absence of analytical frameworks and tools that can reveal connections among science policy decisions, the supply function for science, the demand function for science, and the effective pursuit of stipulated societal outcomes.

Much of our work (as well as that of a number of colleagues) in recent years has begun to consider how to develop such analytical frameworks and tools (e.g., Bozeman, 2003; Bozeman and Sarewitz, 2005; Garfinkel et al., 2006; Guston and Sarewitz, 2002; Pielke et al., 2000; Sarewitz et al., 2000). This work is stimulated by the possibility that scientific priorities and societal needs are poorly aligned in a number of critical areas. The challenge for scholarship, in our view, is (a) to identify particular cases where the promises upon which scientific funding are predicated are not being effectively met, and, more importantly, (b) to show that plausible alternative research portfolios might more effectively meet these promises. The challenge for science policy is to draw on such findings to enable better decisions about the allocation of limited resources.

In this paper we have outlined one way to conceptualize a desirable connection between science policy decisions, science, and social outcomes: via a reconciliation of the supply of and demand for science. We have offered a straightforward method for developing knowledge that could facilitate such a reconciliation, and an example – climate change research – illustrating the method’s application. In doing so, our larger purpose is to challenge science policy researchers and science policy decision makers to seek ways to formalize and to make analytically tractable the neglected, researchable question that must lie at the heart of a meaningful science policy endeavor: how do we know if we are doing the right science?

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