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REVIEW

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Key Points:

- Biases, beliefs, heuristics, and values permeate the progression from sensory inputs to data to knowledge to decisions
- An adaptive framework is presented for the science and policy governance of complex systems
- The framework is discussed in the context of different types of systems or issues of interest in the natural sciences

Supporting Information:

- Supporting Information S1

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From data to decisions: Processing information, biases, and beliefs for improved management of natural resources and environments

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Abstract Our different kinds of minds and types of thinking affect the ways we decide, take action, and cooperate (or not). Derived from these types of minds, innate biases, beliefs, heuristics, and values (BBHV) influence behaviors, often beneficially, when individuals or small groups face immediate, local, acute situations that they and their ancestors faced repeatedly in the past. BBHV, though, need to be recognized and possibly countered or used when facing new, complex issues or situations especially if they need to be managed for the benefit of a wider community, for the longer-term and the larger-scale. Taking BBHV into account, we explain and provide a cyclic science-infused adaptive framework for (1) gaining knowledge of complex systems and (2) improving their management. We explore how this process and framework could improve the governance of science and policy for different types of systems and issues, providing examples in the area of natural resources, hazards, and the environment. Lastly, we suggest that an “Open Traceable Accountable Policy” initiative that followed our suggested adaptive framework could beneficially complement recent Open Data/Model science initiatives.

Plain Language Summary Our review paper suggests that society can improve the management of natural resources and environments by (1) recognizing the sources of human decisions and thinking and understanding their role in the scientific progression to knowledge; (2) considering innate human needs and biases, beliefs, heuristics, and values that may need to be countered or embraced; and (3) creating science and policy governance that is inclusive, integrated, considerate of diversity, explicit, and accountable. The paper presents a science-infused adaptive framework for such governance, and discusses the types of issues and systems that it would be best suited to address.

1. Introduction

Human society faces issues that it has never previously addressed over its evolutionary past. Different perspectives and great uncertainties exist on how to confront these issues. Science can potentially help. Scientists, however, are not independent observers. Like the rest of society, scientists are affected, often unconsciously, by various behavioral influences that affect choices and decisions. We believe that recognizing such influences is essential, because they affect the funding and conduct of science and both the production and the use of scientific information and models. Figure 1 gives examples of what we consider sometimes conscious, but often innate, natural priorities affecting people's choices and decisions.

Many of the issues faced by society, given a current (2017) global population exceeding 7.4 billion, increasingly require the explicit realization of previously hidden costs or externalities resulting from management actions or decisions. Those costs often include long-term, sometimes irreversible, impacts on our environments, on future generations, or on other species. The issues faced often involve trade-offs: for example, the need to decide where, when, and how to extract different resources, given impacts on other resources and environments. Other examples include where to build human infrastructure, how to mitigate disruptions caused by natural hazards or other catastrophic change, or more generally how to address the realities of climate change and land-use change. Clearly, management of natural resources and environments is becoming more complex. This increased complexity and the realities of land-use change are illustrated by the Lake Taupo (New Zealand) case study (cf. Supporting Information). We suggest here that processes

Humans	Needs	Time	Places	Biota	Resources
Myself, my Kids	Safety	The Now	Created by Me	Food, Pets	Air, Water
My Family	Love, Sex	The Near Future	Created by my tribe	Dangerous Creatures	Land, Energy
My Tribe	Esteem	The Next Generation(s)	My Carrying Landscape	Charismatic Biota	Minerals
Other People	Actualization	The Past, the Distant Future	Other Living Places	Other Biota	Environmental Carrying Capacity

Figure 1. Perceptions (by the authors) of some six general types of human priorities, in roughly descending importance. Although separately illustrated, the types of priorities can influence each other in responses to particular situations. Actualization [Maslow, 1943] is the motive and ability to realize one's full potential. A Carrying Landscape [Gumilev, 1990] is the landscape where a person lives most of his/her life, where s/he feels most comfortable and most attached to. Environmental carrying capacity is the capability of the environment to provide resources while absorbing and mitigating pollution.

can be developed that critically examine, and trace with transparency and accountability, the use of science and policy to improve decision making.

Our human welfare, our environments, our resources, and our societal decisions—or lack thereof—are increasingly connected and impact everything else in the ever-more-human earth system that we live in. But have we humans sufficiently examined, individually and collectively, the three fundamental questions of our existence? Where do we come from? What are we? Where are we going? Our thesis in this paper is that such introspection is critically needed if we want to improve both science and the management of natural resources and environments.

Our human minds affect our individual and societal decisions, in our science and in our policies and management actions.

Our decisions are often reactive to our most recent experiences, but are actually tied to lessons of the past through our genetic and cultural adaptations. Collectively, we humans do not have a natural, visceral, ability to consider, far into the future, potential new states of the world and the needs of future generations and a global community. This severely limits the abilities of communities to plan ahead and invest wisely, especially when potential long-term, large-scale, diffusely perceived benefits come at the expense of acutely perceived, short-term, local, or individual costs.

Here we suggest that society can improve the management of natural resources and environments by (1) recognizing the sources of human decisions and thinking, and understanding their role in the scientific progression to knowledge; (2) considering innate human needs and biases, beliefs, heuristics, and values (BBHV) that may need to be countered or embraced; and (3) creating science and policy governance that is inclusive, integrated, considerate of diversity, explicit, and accountable. The systems discussed in this paper are generally complex and encompass humans and their behaviors. They require “complexity thinking” and understanding and managing the duality of “knowing” and “being” [Rogers *et al.*, 2013]. This duality is addressed in Sections 2 and 3 of the paper. Section 4 presents a science-infused adaptive framework that solicits recognition of our BBHV. Potential application of the framework is addressed in Section 5 by bringing in some realities of science and policy governance in the context of different types of systems and issues. As authors and scientists, we bring our own biases and values. We recognize many limits to our synthesis but hope to provide some useful considerations to spur future work. Some aspects of the hopes and limits inherent to the governance that we present are eloquently expressed by *Dennett and Roy* [2015]:

There is a self-limiting aspect to this emerging new human order. Just as ant colonies can do things that individual ants cannot, human organizations can also transcend the abilities of individuals, giving rise to superhuman memories, beliefs, plans, actions—perhaps even superhuman values. For better or for worse, however, we are on an evolutionary course to rein in our superhuman organizations by holding them accountable to individual human standards. This self-regulating dynamic, enabled by accelerating human-machine communicative capabilities, is as unique to our species as human language itself.

2. Knowing: Sources and Process

Here, we provide context on human sources of knowledge and types of thinking, and how they apply (or not) to science and to the management of natural resources and environments. Next, we discuss how human minds and innate sources of thinking affect a natural progression in going from sensory inputs to individual and community knowledge.

2.1. Postnormal Science, Our Thinking, and Our Minds

Our human judgments, decisions, and actions have conscious and unconscious sources. At one extreme, system 1 (S1) thinking is innate, fast, multitasking, and requires comparatively little effort [Kahneman, 2011].

At the other extreme, we use what is often called system 2 (S2) thinking: conscious, logical processing that is slow, serial in nature, associated with language, and that requires great effort. We are cognitive misers [Stanovich and West, 2003]: our brains constantly seek and use shortcuts to minimize mental effort. Consequently, S1 thinking controls most of our judgments, decisions, and actions. Following in the footsteps of behavioral economists and other social scientists, geoscientists, and ecologists have recently argued for the importance of recognizing and deliberately pursuing both S1 and S2 thinking to catalyze scientific progress [Glynn, 2014, 2015; Österblom et al., 2015; Scheffer et al., 2015].

S2 thinking is essential to the methods of “normal” science, where scientists are, ideally, “external observers” seeking to establish a reduced set of “truths” through carefully posed, falsifiable hypotheses; highly controlled, repeatable, experiments; and quality-checked, documentable, often recurring, observations, and measurements. In contrast to “normal” science, postnormal science (PNS) is an integrative science that addresses experiences, judgments, and decisions that are relatively unstructured, poorly controlled, inadequately documented, and transdisciplinary—and where investigators are part of the systems being studied [Funtowicz and Ravetz, 1993]. The PNS framework is a reformulation of the concept of “wicked problems” [Rittel and Webber, 1973] and the attempt to describe the science needed to deal with them. Management and policy experiments, conducted with accountability, traceability, and follow-up to inform and improve the management of natural resources and environments, fit some of the needs of PNS.

Because our decisions and actions are often innately controlled, we need to better recognize, more explicitly incorporate, and sometimes counteract, S1 thinking. Many policy and management issues that are being addressed today are often novel to humankind. Innate responses and actions are therefore often *not* appropriate or optimal for the longer-term, larger-scale benefit of a wider community. S2 thinking is instead increasingly required. Furthermore, the paucity of well-established methods and the need to make decisions and take actions without complete information requires, in our view, greater understanding and management of S1 thinking. Even though it requires greater consciousness and effort, S2 thinking is also affected by human BBHV that affect the choices of abstraction, simplification, and symbol manipulation, and also memory processes. Recognition of the role of BBHV on S2 thinking is also important.

Where do conscious and unconscious judgments, decisions, and actions come from? The authors’ preferred parsing involves four intrinsic sources:

1. evolutionary adaptation (i.e., atavistic responses embedded in our genes);
2. cultural adaptation and communication (i.e., our memes: ideas, attitudes, behaviors, religions, styles, or traditions that can replicate or evolve, spreading from person to person and from community to community within a culture);
3. experiential learning (i.e., trial and error learning that depends on us, not our ancestors or our communities); and
4. logical analysis and deduction (i.e., S2 thinking).

The first two sources, i.e., genes and memes [Dawkins, 2006], have a unique property [Stanovich, 2005]: their replication and “reproductive success” is determined at their own level, and may not always benefit their human vehicles (i.e., us). Reality, of course, is more complex than any parsing and likely involves different combinations of these elements. For example, we are initially conscious of responses acquired through experiential learning until they eventually evolve into innate, fast, responses. We also sometimes use S2 thinking in consciously evaluating and absorbing ideas, lessons, or memes that are communicated to us. Indeed, Dennett [1996; also Stanovich and West, 2003] suggests a different categorization of “minds”: (1) our Darwinian mind (acquired through natural selection of our genes), (2) our Skinnerian mind (conditioned by experiential learning), (3) our Popperian mind (which posits hypotheses and tests them before responding), and (4) our Gregorian mind (which appropriates tools and learning from other people). (The Darwinian mind is named after Charles Darwin and the other minds are named after B. F. Skinner, Karl Popper, and the British psychologist Richard L. Gregory.)

Regardless of which “minds” control our behavior, it would be beneficial for us to differentiate between beliefs and facts, and to understand where our innate responses come from and whether they need to be countered [Wilson et al., 2014]. Many innate responses are essential time and energy savers without which we would be frozen by complexity [Schwartz, 2004; Levine et al., 2015]. Human senses also have adapted to feed us about as much spatiotemporal data as our brains can process.

At the same time, many innate responses are not well conditioned to the issues and to the world of today: (1) a hyper-connected world in which humans have never been more numerous; (2) a world across which the movement of materials, biota, and ideas has never been greater; (3) a world where robots and computers are increasingly outperforming humans; and (4) indeed, a world where human technologies are developing seemingly faster than we can individually adapt to: we are changing the spatiotemporal resolution of the information we need.

PNS enmeshes policy and management actions with science, which in our preferred definition is the structured, traceable, pursuit of knowledge. Knowledge is pursued not only for the intrinsic goal of expanding human understanding, but also with a set of benefits that invariably shape the science conducted. Definition of those benefits, of their boundaries, limits, and potentially adverse effects, if achieved, becomes important. Indeed, we may want to make the best decisions possible to benefit the greatest community (not only human, but also our biotic “cousins”) at the largest spatial scale and for the longest time. But can we really do that? The answers to that question depend to a large extent on our ability to recognize our BBHV and how they affect science and structured processes for acquiring knowledge.

2.2. From Sensory Inputs to Knowledge and Decisions

From sensory inputs to “observations.” We constantly receive sensory inputs, some of which register more strongly than others as a result of evolutionary adaptation and situational circumstances [Buss, 2004]. Sometimes we become conscious of those sensory inputs, at which point they may become “observations” that may be stored in our memory, and retrieved for later use, with different degrees of reliability. Sensory, cognitive, and social biases, and individual and community beliefs, permeate this entire process. At some point, if we become convinced of the reliability or “truth” of our observations (or those of other people), we may consider them as facts. This means that they become part of our knowledge base, without necessarily going through carefully considered, S2-driven, quality-control processes.

From “observations” to “data.” Scientific processes impose structure and documentation methods on the registration, storage, and retrieval of observations, and often on the interpretation and transformation of observations, allowing them to be transformed into “data.” As scientists, we like to think that our collection of data is an “objective” process. There is subjectivity, however. We make choices in what observations are paid attention to, what instruments are chosen to collect and store those observations, and what accuracy and precision we consider suitable. Long-term goals, short-term objectives, convenience, and funding all influence our prioritization decisions in the collection of “data.” Subjectivity is exerted also through the “simplifications” and conveniences imposed by our structuring processes and our methods used to register and transform observations and store them as data [Daston and Galison, 2010]. Mental models [Jones et al., 2011], community influences, and “tribal” associations (including professional/disciplinary tribes) pervade this process.

From “data” to “information” to global “hyper-connectedness.” We get “information” when we further pick, organize, or structure “data” and associated metadata, and produce something that we *sense* or *realize* can be useful to us or to others. The processing of data and the consequent development of “information” are affected by various human beliefs, biases, heuristics, and values. They influence our choices of data and data-processing methods (algorithms, theories, software, and hardware). The “information” developed becomes an evolving “model” of reality that can be further transformed through numerical modeling and other mechanisms, and that can evolve further (1) as it relates, associates, compares, and aligns with other information, (2) as it is molded and used by different communities, (3) as it is placed on a printed page or in a digital repository, and/or (4) as it is archived and transformed into networked information. The current extent and accessibility of networked information has never been encountered by human society during its evolutionary/cultural adaptation. Our “genes,” “memes,” cultural traditions, and even our experiential learning processes are not well suited to help us interact with the complex, dynamically evolving, human “ecology” of networked systems and information [Weinberger, 2014]. In the authors’ view, human society has not well adapted yet to the “augmented reality” offered by numerous apps or gadgets (e.g., virtual reality headsets), or to the virtual environments increasingly linked to various modeling and processing tools [Lin et al., 2015]. This point can be disputed. Children for example have shown instinctive ability to use aerial photos to find their location [Blades et al., 2004].

From “information” to “knowledge.” Knowledge is essential to decision making, whether the decisions are made by a single individual, a group of experts, or a broad community. What is knowledge? For our purpose, knowledge means “knowing” something is true and having a justified belief in its truth [Plato, 369 BCE; Ichikawa and Steup, 2014]. Obtaining “knowledge” means that information becomes “internalized,” that an alignment occurs between preexisting beliefs and information. Old beliefs become reinforced or, more rarely, new beliefs emerge. Knowledge development is also often linked to simplifications and abstractions of available data and information. More importantly, having knowledge at the level of an individual or at the level of a community means that decisions may now be made.

Prior beliefs and biases affect our development of knowledge. People rarely accept facts and highly objective information provided by others, especially if it requires changes in their behavior, unless they can absorb and align the information with their belief and value systems [Fagin and Halpern, 1987; Stanovich and West, 2003; Heylighen and Chielens, 2008; Ariely, 2010; Chabris and Simons, 2010; Stanovich and Stanovich, 2010; Stanovich, 2013]. Logical argumentation rarely convinces people to change their beliefs [Anderson et al., 1980; Anderson, 1983]. Instead, people often “cherry pick” explanations and “facts” that match their beliefs and value systems. Scientists are not immune to this behavior. The idealistic assumption is that science is value-neutral, that it can provide information for policy and decision-making, and that individual or societal values and preferences only occur on the policy and management side [Sarewitz, 2004]. As Darwin [1857] put it: “A scientific man ought to have no wishes, no affections, a mere heart of stone.” In reality, there are numerous examples of scientists being very human in their decisions and choices [Oreskes and Conway, 2010; Jasanoff, 2014].

“Bias” is often a pejorative term. In the authors’ view, BBHV are not necessarily something “bad” that *always* needs to be countered. BBHV have been key to our evolutionary success, as a species and as individuals. Our reproductive success is attested to by a human population now exceeding 7.4 billion. Our technological success is demonstrated by the hyper-connected planet that we have created. Perhaps our greatest successes are in the evolution of our consciousness, our ability for self-reflection, and our ability to analyze and modify our behavior. BBHV generally reflect behaviors, traditions, simplifications, and shortcuts acquired during our evolutionary or historical past that have led to our success. Some of the issues of today, though, have never been encountered or adapted to. They therefore require an explicit recognition and evaluation of biases and beliefs.

Large-scale complex systems, such as the natural and environmental systems focused on herein, commonly have timelines and scope that ideally require knowledge development, decision making, and follow-through not by single individuals, but rather by entire communities and institutions. The processes needed to translate, transform, and aggregate the knowledge of many individuals into community knowledge are themselves susceptible to simplifications, biasing of many forms, and group beliefs. In turn, current or past community or institution beliefs influence individual beliefs. Group dynamics affect knowledge gathered and decisions made at multiple levels and scales of “community.” Improving the management of large-scale complex systems transcends the investigative, analytical, or synthesis skills of any single scientist. It requires scientific and institutional teamwork and follow-through, as well as the engagement of stakeholders and members of the public [Voinov et al., 2014]. BBHV need to be explicitly recognized in this process. But first, let us consider how some of our human characteristics and sensibilities can actually enhance the science and management of complex systems.

3. Being: Utilizing our Emotions, Recognizing our Limitations

We join many authors [e.g., Rathwell and Armitage, 2016] in recognizing that society will not be able to optimally address many of the big problems and issues that it faces if it does not integrate the “two cultures” [Snow, 1959], the sciences and the humanities. Our emotions and different types of thinking need to be taken into account in seeking workable solutions. Understanding who we are, where we come from, where we are going, and recognizing our BBHV are examples of the integration and analysis that need to occur.

3.1. Art as a Humanizing Frame for Analysis and Synthesis

So far we have examined our different “minds,” the origins of our biases and beliefs, and how they permeate the progression from the sensory inputs we receive, to the information we provide, to the knowledge



Figure 2. Paul Gauguin's (1848–1903) painting entitled: "Where Do We Come From? What Are We? Where Are We Going?" Oil on Canvas (1997–1898; 139.1 cm × 374.6 cm). Museum of Fine Arts, Boston. Tompkins Collection—Arthur Gordon Tompkins Fund, 36.270. Photograph © (2017) Museum of Fine Arts, Boston.

that we create, individually and as a community. An artist's expression provides an analogy. First, the artist draws on the past: a wealth of genetic, cultural, and community inheritances, previously buried feelings and emotions, and some individual learning (usually experiential). Second, the artist meets the present: a diversity of sensory inputs condition, frame, and affect the artist's creative process. Logic, simplifications, external constraints also play a role. Third, the artist focuses on the future: feelings to be brought out, realities to be shaped, points to be made, audiences or colleagues to be impressed. Through the realization of a creation, the artist, often innately, answers three basic questions: (1) where does she/he come from? (2) what is she/he? and (3) where is she/he going?

Society may shape, or be shaped by, the artist's creative process. Will the artist's tribe or community relate to the art by sensing a commonality of (1) past experiences or emotions, (2) present feelings and constraints, or (3) future aspirations and desires? Will the tribe or community relate to the artist's creation; contribute its own set of expressions or realizations; augment, complement, diminish, or destroy the artist's individual expression? The artist's creation is now part of a community stage with its own drivers, rules, and assessments that modify perceptions of the artist's creation, even as those perceptions keep evolving in the minds of the artist and of the community. Are there parallels with PNS?

A painting considered Gauguin's lifetime masterpiece relates to our analogy (Figure 2). It has symbols, structure, and direction: it should be "read" from right to left, from birth to apotheosis (the picking of the apple of knowledge) to death, and possibly reincarnation or transference to some other state. It evokes emotions in its viewers, but also solicits analysis and synthesis. Interpretations/realizations created in the minds of viewers likely have commonalities, but also differences, and probably leave behind ambiguous or impenetrable aspects.

The painting illustrates the inescapable reality of our biases and beliefs. First, we need myths and art to unify us, to help us transcend our individual cycles of birth to death, to give greater meaning to our lives. Second, we like to think that we are separate from nature [Botkin, 2000], but we are not. Compared to other animals, our processing brains may be able to handle greater symbolic complexity, greater contextual complexity, and may also have greater abilities to self-reflect and create higher-order evaluations of initial preferences. Those remarkable abilities, however, can sometimes result in our being less rational than other animals [Stanovich, 2013]. Following on this, we are driven by exceptionalist beliefs in ourselves (and our tribes). Noting this, the American humorist Garrison Keillor satirically opens his popular radio show with: "Welcome to Lake Wobegon where all the women are strong, all the men are good looking, and all the children are above average." (Lake Wobegon is a fictional place; https://en.wikipedia.org/wiki/Lake_Wobegon.) Another point that Gauguin's painting makes for us is that our cultural, material, and technological differences are like clothes on our backs: they are there for all sorts of reasons (e.g., comfort, safety, fitting in, displaying status), but they don't negate the basic commonalities driving our existence and behaviors.

Art provides a sensory experience that can help us relate to each other, to our individual humanity, to our "tribe," but also to greater things. Art "speaks" to our S1 thinking: we often have visceral reactions that can

help us focus on a key message. “The Scream” by Edvard Munch, or Pablo Picasso’s “Guernica,” does not leave many people neutral. Should science and communications learn how to speak directly to people’s emotions? The behavioral sciences have learned how to do that and have created an extremely successful enterprise: the advertisement industry. Behavioral scientists have also found ways to “nudge” people into making specific decisions (e.g., donating their organs), sometimes by providing them with defaults perceived to be beneficial while retaining individual liberty of choice [Thaler and Sunstein, 2008]. A science of managing behavioral and cultural change, from individuals to large populations, has now been created [Wilson et al., 2014]. This includes the changing of social norms to better address environmental challenges [Kinzig et al., 2013]. In the authors’ view, the development of these behavioral nudges or soft-controls has a few missing elements. First, the people impacted don’t necessarily recognize that they are being manipulated, however softly, for their individual welfare, for someone’s profit, or for some perceived greater public good. Second, BBHV don’t just affect decisions or the implementation of policies, they also affect the conduct of science. How can the “right” policies be devised, if the scientific truths, tools, and assessments of tradeoffs supporting given policies are flawed by the BBHV of the funders, producers, and interpreters of science? Even “normal” science has previously been seen as socially constructed [e.g., Latour and Woolgar, 1986; Latour, 1988]; PNS suffers from many of the same problems of “social construction,” but because of its characteristics, it is even more affected by human BBHV.

Science is closer to art than scientists are usually willing to admit. Aren’t sentiments applicable to science? Don’t scientific findings “blossom” in our mind prior to our realization of what we are doing? Don’t we suffer from “confirmation bias”? Art and science can both involve the seeking of recognition—and of those metaphorical clothes that cover us. The “trade” of science can affect its nature: its choices, conduct, and results, can be biased by economic or political drivers. The traditional models for scientific peer review that were developed during the era of “curiosity-driven science” seem now much more subject to manipulation and biases in the era of PNS and mission-oriented, issue-driven science, and in the provision and use of scientific advice for policy [Funtowicz and Ravetz, 2015].

Society should strive for the development of science-based, open, transparent, accountable policies that recognize BBHV both in the conduct of science and in the development of improved policies. However, recognizing human emotions and BBHV, and properly compensating for them when needed, does not mean that they can or should be eliminated. Indeed, human senses can be used and engaged for many long-term, benefits, including for scientific discovery and knowledge acquisition [Österblom et al., 2015]. Creative expression and role-playing can help us come together as communities while also allowing different priorities or beliefs to be represented in low-threat, decontextualized settings. Fuller engagement of our human senses and bodies may help us gain understanding and knowledge faster and more deeply.

We need to answer the questions “Where Do We Come From? What Are We? Where Are We Going?” if we want to better manage our natural resources, our environments, and ourselves. We may also need to keep in mind Gauguin’s question when painting his masterpiece:

Where does the execution of a painting begin, and where does it end? At the very moment when the most intense emotions fuse in the depths of one’s being, at the moment when they burst forth and issue like lava from a volcano, is there not something like the blossoming of the suddenly created work, a brutal work, if you wish, yet great, and superhuman in appearance? The cold calculations of reason have not presided at this birth; who knows when, in the depths of the artist’s soul the work was begun unconsciously perhaps? [<http://www.gauguin.org/where-do-we-come-from-what-are-we.jsp>]

3.2. Biases, Beliefs, Heuristics, and Values

Biases represent tendencies to (1) believe in or pay attention to some observations, ideas, or people to the detriment of others; or (2) make decisions or act in innate ways. Heuristics are innately derived “rules of thumb,” mental shortcuts or simplifications that help us navigate through the complexity of the world and its relationships [Levine et al., 2015]. Similarly, “values” are conceptions of the desirability, undesirability, or relative prioritization or importance of actions or things.

Biases, heuristics, and values are conditioned in us. They allow our conscious or innate judgments, decisions, and actions to be optimally effective and efficient in our interactions with our environment, with other

species, and with other people [Morewedge and Kahneman, 2010]. To be effective, they cannot evolve or change very fast; otherwise they have difficulty taking hold or are not well-anchored [Inglehart and Welzel, 2010]. Values are sometimes considered to change on a generation by generation time scale (faster than the genetically acquired subset of biases and heuristics).

Belief is related to biases, heuristics, and values, in the sense that anchoring has now engendered (1) an acceptance or a conviction that some thing or some statement is true or real; or (2) a trust, faith, or confidence in a set of values and attitudes, in a tradition, in a thing or concept, in a “tribe” or in a person, including oneself (rephrased from the online Oxford English Dictionary).

What is perhaps the most important bias or belief that warrants attention in the structured processes of PNS? Our “exceptionalist bias” is probably most important for both positive and negative reasons. It is defined by our “belief” in ourselves and in our “tribes.” It gives us “drive.” It also gives us security by strengthening our “tribal” inclusion and appropriation of beliefs and cultural norms. It has been key to our reproductive success as a species and also to many of our technological successes. But will it benefit our postnormal future? Does the “groupthink” [Janis, 1972] that it often engenders provide the optimal larger-scale, longer-term, greater community solutions that we need? Does it allow us to accept that our “tribe” may be on a wrong path, that we may be missing something really important, that “obvious” actions may result in damaging consequences? Does it leave us enough humility to listen to the narratives and perspectives of other people? Does it give us the humility to accept that sometimes doing what is immediately best for us, but damaging for other species or other “tribes,” may not be best for the long-term large-scale survival of our descendants?

Thinking about these questions, even if they remain unanswered, is important. They relate to the greatest progress and distinction of our species, our ability to think logically and self-reflexively and to make higher-order evaluations of our judgments, decisions, and actions. Such higher-level evaluative and critical thinking is essential to the optimal management of problems or issues that we haven’t experienced and adapted to in our past [Wilson et al., 2014]. Such thinking solicits recognition of our BBHV and of their sources. Many of the biases and heuristics are discussed by behavioral scientists [Tversky and Kahneman, 1974, 1981; Kahneman and Tversky, 1979, 1984; Stanovich, 2010], are being investigated in neurobiology [De Martino et al., 2006], and are being used to suggest critical improvements in the implementation of social policies [Jolls et al., 1998; Thaler and Sunstein, 2008] and negotiation [Lewicki et al., 2011: Chapter 5 on anchoring and framing biases]. They have led to a revolution in economic theory through the creation of the field of behavioral economics [Thaler, 2015]. The management of natural resources and environments, the mitigation of natural hazards and other risks, and the conduct of science also stand to benefit from greater recognition of the role of BBHV in affecting our behaviors [Brugnach et al., 2008; Johnson and Levin, 2009; Brugnach and Ingram, 2012; Glynn, 2015; Österblom et al., 2015].

In addition to the BBHV mentioned so far, there are many others that can potentially affect the conduct of PNS:

- confirmation bias [Nickerson, 1998]; and framing and anchoring biases that depend on the ways information is presented [e.g., Spiegelhalter et al., 2011] or on which pieces are mentally anchored;
- loss aversion bias (i.e., sensitivity to potential losses exceeds that of potential gains);
- cognitive discounting (e.g., we focus on the visible rather than the invisible);
- preferential valuing of the present over the future, and of the future over the past;
- prioritized attention to acute rather than to gradual changes (i.e., “creeping normality”);
- an innate preference for stability and steady-states;
- an overwhelming belief in causality (i.e., “God does not play dice” to paraphrase Einstein); and a tendency to believe in single rather than multiple causes (and often, through human hubris, in human rather than nonhuman causes);
- a constant seeking for patterns, but a frequent inability to connect the sources of our actions (e.g., extraction and consumption of resources) with their consequences (e.g., waste production);
- a preference for putting the immediate needs of ourselves, our families, and tribes over the needs of a wider community, or over future needs;
- biases and beliefs engendered by group dynamics (e.g., posturing and differentiation, attention seeking, following the confident leader, “groupthink”);

- simplification and efficiency biases (e.g., binary bias and other reductionist biases; preferential use of existing tools over new ones; focusing on subsystems that are within the limits of individual minds).

The BBHV listed above have received insufficient investigation, if any—especially in their influences on the science and management of natural resources and environments. Nevertheless, some suggestions and approaches have been discussed to recognize and potentially compensate for them [Hämäläinen and Alaja, 2008; Glynn, 2014, 2015; Hämäläinen, 2015; Voinov *et al.*, 2016]:

1. examining the negative space of information constructs;
2. assessing the past and the future of situations, not just the present;
3. obtaining diverse and open perspectives;
4. red-teaming (a “red team” is an independent entity that aggressively fights groupthink and challenges another group or organization to improve its effectiveness and/or thinking);
5. using structured, accountable, traceable, and transparent processes for information/knowledge gathering, participatory interactions, and decision-making;
6. ensuring adaptive follow-through on decisions or actions taken;
7. following a principle of continuous learning, review, and reflection [Rondinelli, 2013]; and
8. using video training or other instructional methods, and especially interactive video gaming to help reduce specific cognitive biases [Morewedge *et al.*, 2015].

Hämäläinen [2015] also considers practical response measures and suggests that “systems thinking” needs to evolve to “systems intelligence.” In that context, Critical Systems Heuristics [Ulrich and Reynolds, 2010]

Table 1. Some Problematic or Incorrect Assumptions Resulting from Human Biases, Beliefs, Heuristics, and Values (BBHV)

- The past does not inform the future, and earth systems science has no relevance to resource allocations or to the emplacement of human infrastructure. The records of tree rings, paleoflood deposits, tsunami deposits, historical accounts of infrequent natural hazards (earthquakes, hurricanes, floods, debris flows, volcanic eruptions, fire) can all be ignored.
- Discount the future and address only immediate, local, human needs (or threats): human ingenuity will always rise to meet the needs of future generations. (And population growth is not a problem since it increases the gene pool and produces more talent that will solve all problems.)
- Ecosystems (or parts thereof) do not have lagged responses: policy or management actions have only immediate effects.
- Believe what you see, ignore what you do not: the invisible (e.g., groundwater, microbes) can be ignored when constructing models. (Groundwater and surface water are not connected and do not impact each other (or water quality). And only highly visible contaminants, or immediate acute health threats, matter: invisible contaminants, or slow-acting threats, do not.)
- Pests, parasites, and predators have no useful functions, are always evil, and should be eliminated. Pets and charismatic biota are the only species, apart from humans (and food-providing biota), worth worrying about.
- Because this is what people care about, the study of biotic species that are charismatic (or serve as a food or recreational resource) can be assumed to inform the assessment of environmental conditions in a region.
- Nature provides only benefits to humans (whomever, wherever, and whenever those people may be); the disservices of nature do not need to be included in the design, quantification, and valuation of ecosystem services. (And the services do not include provisioning of mineral and energy resources.)
- No modern day actions have irreversible consequences: resources are infinite, species can be resurrected, and past environmental conditions can be restored.
- Humans are separate from nature, and their enterprise is superior to nature's. (Build the infrastructure, construct the levees, drain the wetlands.)
- John Muir [1911] was wrong to say “When we try to pick out anything by itself, we find it hitched to everything else in the Universe.” One person's actions or one's tribe's actions have no meaningful impacts on anything else, or on other tribes. (In any case, the global community, or other human tribes, will take care of themselves: our tribe is superior and has manifest destiny.)

The above assumptions, based on the perspectives of the authors, can influence the pursuit and conduct of science (including the production of models) and the implementation of science into policy.

provides a reflective framework and tools that enable system explorations through a set of “boundary questions.” The questions test sources of motivation, knowledge, and legitimacy to judge how they are (or ought to be) applied to determine social roles (i.e., types of stakeholders), specific concerns (i.e., types of stakes), and key issues. Answering the questions helps determine system biases and simplifications.

Why should earth system scientists care about BBHV? Why study the behavioral biogeosciences [Glynn, 2015]? The reason is simple. Human behaviors, prioritizations, and attitudes affect everything that humans do, including the conduct of science (cf. Table 1 for some commonly used problematic or incorrect assumptions).

How can the management of natural resources and environments be better informed by science and thereby improved? The use of structured processes and adaptive learning from policy and management experiments is one critical element in our view. Recognizing and possibly countering BBHV in such processes is another critical need. Other elements include the need for inclusivity, transparency, traceability, honesty, and integrity, accountability, and follow-through, all within a human context of organization, coordination, engagement, and ownership. The next section addresses these needs.

4. A Science-Infused Adaptive Framework

Here, some of our insights gained on “knowing” and “being” are brought forward in the design of a science-infused adaptive framework for science and policy governance. Subsequently, we present some of the advantages and limitations of the framework and the characteristics of situations where a science-infused adaptive framework might be best applied.

4.1. Design of the Framework

We have discussed the sources of our human judgments and their behavioral controls and consequences and the process of going from sensory inputs to knowledge and decisions. Here, we suggest a cyclic framework that aims to:

1. generate information;
2. recognize and possibly adjust or counter biases and beliefs;
3. create knowledge and understanding of complex systems;
4. enable and encourage the recording of detailed biophysical and social predictions—honest enough to explicitly consider the potential “losers” as well as the likely “winners” and of any decision or action;
5. improve the management of complex systems—through follow-up, review, and auditing of the results of predictions, and by learning from and remembering the lessons of policy and management experiments. (We recognize that the management may require long time scales and multiple policy-development phases.)

Our framework has similarities with the participatory processes, structured decision-making, and the “learning-by-doing” aspects of adaptive management [Williams *et al.*, 2009; Allen *et al.*, 2011; Tyre and Michaels, 2011; Williams, 2011; Craig and Ruhl, 2013; Scarlett, 2013; Galat and Berkley, 2014; Allen and Garmestani, 2015]. It differs in that it explicitly seeks: (1) recognition of beliefs and biases, (2) recognition and prediction of “winners and losers” in potential decisions, and (3) thorough documentation of predictions and ex-post review or postaudits. Like adaptive management, in addition to having an “improved management” aim, our framework also has the more diffusely felt objective of seeking knowledge generation and retention by society, through participatory processes [Jasanoff, 2004, 2013; Meadow *et al.*, 2015], “soft-systems thinking,” and social learning [Cundill *et al.*, 2012].

The framework provides a structure for greater transparency, accountability, and inclusivity of perspectives. It addresses the reality that human decisions often have poorly anticipated consequences (e.g., the introduction of rabbits in Australia); it potentially allows for thoughtfully considered corrections, if continuity and accountability can be socially ingrained. At a minimum, it insists on recording the definitions and boundaries of the systems that it addresses, as well as the explicit predictions that it makes. This means that greater knowledge and understanding could be gained and retained, even if management objectives are not achieved. Our science-infused cyclic framework is highly idealistic (Figure 3). Implementation of its components may only be partially achieved in practice, depending for example on the magnitude



Figure 3. A science-infused adaptive framework for knowledge generation and decision evaluation. The cycle is started by the setting of goals, is adaptive, and can be exited when goals are attained.

of consequences, on the availability of resources, and on demonstrated usefulness to participants and stakeholders [Lemos and Morehouse, 2005].

A structured progression. There is an established progression to (1) acquiring data—usually on the basis of a preexisting mind-frame, (2) structuring and processing the data into useful information, (3) aligning the information and beliefs to gain knowledge that can then be used to (4) assess, predict, decide, and take action(s), the consequences of which are (5) monitored, evaluated, and compared to the earlier predictions and used to update existing conceptual models. At which point, the cycle (Figure 3) can iterate again to seek knowledge and improved management of the complex system/issue.

Our section on “knowing” (Section 2) discussed the first three steps of this cycle; and the section on “being” com-

mented on the sensibilities that can help unite us, help us engage in higher-order evaluative thinking, and help us discover the innate, and sometimes conscious, BBHV that affect each step of our cycle. We also listed practical strategies that could be used to try to recognize and assess those BBHV, and counteract them if needed. In essence, our cycle seeks to enhance the use of critical and evaluative reasoning (S2 thinking), not only at the level of individuals but also at the level of the engaged community, even while it recognizes that S1 thinking and reactions are essential to consider in obtaining engagement. Community and stakeholder engagement is critical, not only to bring the diversity of perspectives needed for optimal decision-making, but also to ensure that knowledge generated gets used wisely and is not lost.

This decision cycle is quite natural when considering individual behavior, but will likely be more difficult to apply at a group or community level, and to larger-scale projects and general decision making. Previous work on group dynamics, such as in participatory modeling [Voinov and Bousquet, 2010], has often assumed that structuring an ordered process is hardly possible because of the unpredictable effects of stakeholder values and participation. Here, our assumption is that by recognizing and considering S1 thinking and behaviors at all stages, our ordered cyclic structure can apply and be useful even for large projects that involve group decision-making and numerous, perhaps conflicting beliefs and values. Our argument is that our framework can be used to recognize, and possibly reconcile, differences among stakeholders and to guide knowledge generation and improved management in a structured, traceable, and productive way. Alternatively, our framework could be used to bring out irreconcilable differences before too much time and effort is wasted on participatory processes that are unlikely to generate either improved management or improved knowledge.

Although our process is represented as a cyclic linear progression, it is adaptive. Short-circuiting the loop or going back to “redo” an earlier stage is certainly possible and may be essential. The outcomes of the process may be “path-dependent,” as is recognized in model-supported problem solving and operations research [Hämäläinen and Lahtinen, 2016; Lahtinen et al., 2017]. For example, while translating information into knowledge, it may be realized that existing data are insufficient and that it is essential to go back and acquire new observations and data before making decisions. [This is demonstrated in the Lake Taupo (New Zealand) case study, analyzed through our framework; cf. Supporting Information.]

Conceptual models, mind-frames, and *a priori* knowledge drive our cyclic process. By definition, these are not “objective.” Engaged groups and individuals need to establish the *a priori* knowledge base (e.g., functional relationships, causalities, effective, or likely processes) in structured, documented, traceable ways. They can (1) trust (T) individual experts or participants to contribute their *a priori* knowledge base, and/or (2) join (J) an effort to develop a group understanding of the *a priori* knowledge base. This is our Trust and/or Join (TJ) decision and action process. Establishing a group conceptual model likely involves a combination of T and J. Next, understanding is established of what types of data are needed over what spatial and temporal scales, and what data can practicably be obtained. Again, the group can either Trust individuals to obtain the data and/or engage in Joint-Fact-Finding. TJ processes can similarly be used, explicitly, transparently, traceably, in all the other stages of our framework.

Judge, decide, act. Individual and group behaviors become even more important as the stakes become higher. BBHV and S1 thinking can overwhelm S2 thinking, or the priorities of individuals may not be aligned with the large-scale longer-term priorities and needs of a wider community. This is especially true if the needed behaviors and situations have not been frequently and acutely experienced through our individual lifetimes and/or through our evolutionary and cultural adaptation [Stanovich, 2005, 2010, 2013; Stanovich and Stanovich, 2010; Glynn, 2014]. Ideally, decisions and actions are taken on the basis of information analyses, modeling syntheses, exploration of scenarios, and/or explicit recognition and guidance provided by group or individual beliefs.

Predictions are essential here: expected system outcomes of decisions/actions taken need to be made explicit and detailed. Definitions of what was assumed, considered, or not considered are also needed. Predictions need to indicate the expected type and magnitude of impacts and the temporal and spatial scales of the impacts. An explicit prediction is also needed not only of the expected “winners” of decisions and actions taken, but also of potential “losers.” (“Winners” and “losers” may become apparent, and are defined throughout this paper as resulting from the consequences of decisions or actions including the potential distribution of gains and losses across diverse communities.)

Evaluate and reevaluate. This final step in our cycle involves analysis of the decisions made and actions taken based on observations of consequent impacts. The analysis is subject to human and societal bias, but treats decisions/actions taken, and the consequent observations and postaudits, as the equivalent of a scientific experiment and an opportunity to gain system understanding [Rondinelli, 2013]. The understanding then leads to an evaluation or reevaluation of the models constructed and of the supporting knowledge-base, and depending on community and institutional objectives and willingness, new iteration(s) of our cyclic framework.

One important point: implementation of the framework could potentially reflect our human causality bias, if used to narrowly examine actual versus predicted system states only after policy action(s). Trend analyses and other statistical analyses of baseline conditions and of past system states are essential in recognizing stochastic variability (or nondeterminable causes). More generally, availability, access, and careful continued analysis of long-term datasets, collected with well-documented standard protocols, are essential to the improved management of natural resources and environments [Lovett *et al.*, 2007; Lins *et al.*, 2010; Magurran *et al.*, 2010].

4.2. Best practices for implementation of the framework

The recent initiatives for Open Access to scientific data and models are admirable (e.g., <https://www.whitehouse.gov/blog/2013/02/22/expanding-public-access-results-federally-funded-research>.) In our view, the coproduction of knowledge from policy-decision and management-action experiments requires a similar level of accessibility, traceability, and accountability not just in the conduct of science, but also in the conduct of policy and management actions. Consequently, we suggest the development of an “Open Traceable Accountable Policy” initiative with the following characteristics:

1. Management and regulatory entities that claim to have a scientific basis for their decisions and actions ought to make accessible, documented, traceable predictions (as well defined and as detailed as possible and with appropriate uncertainties given) of the expected consequences of their decisions and actions.

2. To improve knowledge and management of complex systems, these entities also ought to monitor consequences of their decisions/actions, and be accountable through follow-up analyses, reviews, and postaudits of their predictions.

We also suggest three best practices for the application of our adaptive framework. The first is to *have meaningful, mindful diversity*. The process of integrating individual perspectives into a few group perspectives can be used to ascertain and engage the external community, assuming that the group has sufficient diversity to represent the external community. That diversity is essential. The perspectives presented, or any consensus achieved or judgments developed, should aim to reflect the best informed, most reflective, diverse, transparent, and structured melding of voices, of sources of information, and of acknowledged beliefs. The wisdom of a “crowd of independent broad-thinking minds” is sought [Surowiecki, 2005], rather than the “madness of a herd” [McKay, 1841; Petsko, 2008]. Diversity of perspectives is also needed to ensure acceptance of process and actions by a broader community.

The second is to *establish and document core principles*, agreed upon by participants and communities, early in the process. This is essential to the operation of our adaptive framework [Voinov and Gaddis, 2008; Voinov and Bousquet, 2010; Hughes et al., 2012; Voinov et al., 2016]. The principles establish rules of engagement and behavior throughout the process.

The third is to *use optimal methods and approaches*. Methods and approaches need to be developed, and used, that seek to minimize the effects of BBHV while still retaining their usefulness, comprehension, and acceptance by the engaged participants. The techniques include quantitative storytelling, “sensitivity auditing,” and appropriate use of numerical models [Saltelli and Funtowicz, 2014]. Other structured approaches can be used such as the NUSAP (Numeral, Unit, Spread, Assessment, and Pedigree) system [van der Sluijs et al., 2005] for describing and communicating uncertainty in science for policy considerations. In addition, participatory modeling techniques [Voinov et al., 2016] aim to help participants “internalize” information and explore possible future scenarios and outcomes. Efficiently engaging participant senses and attention, for example by using visualization tools [Glynn et al., 2011; Spiegelhalter et al., 2011; Bishop et al., 2013], also remains essential.

4.3. Perceptions and the Issue of Winners and Losers

Often, it is not the evidence shown or the exact tools or methods used that are important, but rather the perceptions of stakeholders regarding how the evidence is gathered, how the tools are used, who is engaged, and whether they feel that evaluation, decision, and action processes are fair and credible. This is illustrated by the issue of “winners” and “losers.”

The laws of thermodynamics tell us that in closed systems gains are always balanced by losses. Entropy (i.e., disorder and information loss) always increases with time in closed systems. In many cases, the “losers” of a decision, action or process are either ignored, or go unnoticed, or their losses are deliberately diffused to allow gains by a smaller or different community. If everybody wins, it likely means that somebody was forgotten, most likely at a distant place in either time or space (e.g., our children or subsequent generations). It can also mean that we have ignored harm to our biotic nonhuman “cousins.” We need to recognize that we live in a climatically, ecologically, and socioeconomically “teleconnected” world, where actions in one area of the planet can impact separate and distant regions, too often without our knowledge and understanding of the connections [Liu et al., 2013].

However, because our human minds do not receive them well or with equanimity, conveying negative messages is often very unproductive. Loss-aversion bias, our greater sensitivity to potential losses than to potential gains [Kahneman and Tversky, 1984; Kahneman, 2003], increases the difficulty of finding understanding among stakeholders who potentially face near-term losses, at least if they rely on their past experiences and existing “frames” of perspective. By “reframing” the picture, and pointing out new potential “wins” that they might not have previously considered, it is sometimes possible to create and define opportunities for what is often referred to as “win–win” conditions [Jaeger et al., 2012]. Relevant stakeholders are then more likely to take or accept necessary actions for the longer-term good of a wider community. The term “win–win,” however, displays a binary bias simplification while also assuming, somehow, that “everybody” wins, which is unlikely. In our view, by being honest and transparent instead about the potential losers, by trying to define them and predict their potential losses, we may gain greater credibility in the long run by and for a

greater community. We may also want to consider that, from an economic perspective, wins could accrue from the conversion of inefficient systems to more efficient ones.

There is extensive literature available on how to communicate messages about climate change [van der Sluijs, 2005; Klopogge et al., 2007; van der Sluijs and Wardekker, 2015; Van der Sluijs et al., 2015]. In most cases, focusing on possible gains and reframing losses can help. We may have some losses in terms of current, local, and economic conditions. However, present losses may also result in future wins and may possibly benefit a wider community for the longer term, if we clean up our environment, improve our health and education, preserve biodiversity, create new types of enterprise and jobs, decrease crime rates and violence, and reduce population growth for our species.

Hardin (1968) illustrated how difficult it is for us to share and maintain common resources, without having the natural instincts of individuals cause a degradation of the Commons. His message was quite negative: the commons were always degraded or lost if unrestricted access was granted to individuals who in many cases tended to maximize their own immediate benefits. Elinor Ostrom, however, received a Nobel Prize for understanding the need for “bottom-up” community planning and the importance of cultural norms that could help avert the “Tragedy of the Commons” described by Hardin [Dietz et al., 2003; Ostrom, 2010a, 2010b; Vollan and Ostrom, 2010; Ostrom et al., 2012; Kinzig et al., 2013].

Public participation and engagement, honesty and transparency, and the sense that solutions are not just imposed top-down are essential to gaining credibility and buy-in from engaged communities. However, we often deceive ourselves. Getting longer-term, greater-community wins can happen only if the system being dealt with, and its reference points, are changed or expanded that is, if its “boundaries are spanned” [Bressers and Lulofs, 2010]. Generally, optimal management solutions are not invented to achieve better results within the same system. Instead there is usually a substitution of one system for another, going from a usually smaller and less inclusive system to a more open one, or by including other factors, values, perceptions, and priorities in our consideration.

Bottom-up solutions created through the engagement and ownership of local communities and tribes work best when both the problems and their solutions are local, immediate, and acutely felt. As the problems and the potential solutions increase in scale (in terms of time, space, communities, and processes that need to be considered), local “ownerships”, and perspectives tend to get diluted, and harder and less efficient to engage. Consequently, there is a temptation to use top-down controls (e.g., laws); they have demonstrated efficiency in addressing universally felt and immediate critical issues (e.g., burning or unfishable rivers, irritated eyes and stinging throats).

Nonetheless, top-down controls imposed without meaningful local participation, engagement, and ownerships are probably less effective and harder to get follow-up and buy-in for, especially when the problems and issues are less clear, more complex, and involve the longer term, [Gregory et al., 2006]. This is particularly true when the controls, policies, and laws are not reflexive, scale-sensitive, and adaptive [Garmestani and Benson, 2013]. We next discuss practical examples of this reality.

5. Assessing System/Issue Characteristics for Improved Governance

Because of our disciplinary traditions and experiences, the focus of our paper is on systems and issues that relate to natural resources, the environment, and related hazards. In our view, improving the management of these systems and issues requires (1) increasing knowledge of the complex systems that humans and other species depend on, and (2) using this knowledge to improve management of those systems and issues. Not all systems and issues require the science-infused adaptive framework presented in Section 4. Determining whether the framework is needed and to what extent depends largely on assessing the characteristics of given systems or issues. Understanding how science is perceived, and consequently used for policy making, is also needed for our discussion.

People see science through two different mental frames, as either (1) an accumulation of truths and tools usually beneficial to those who use them, or (2) a structured, traceable, process infused with critical thinking and analysis. These frames have consequences for the optimal governance of science and policy for different types of systems or issues. Science as an “accumulation of truths and tools” feeds into the demarcation model of science and policy. It differs from the “science as a process” frame that pervades our

cyclic framework. What are the characteristics of systems and issues for which a demarcation model may be most appropriate?

Fast, frequent, painful, common does best for demarcation. The demarcation model of science and policy, where each side is separated by imaginary or institutional walls has often been criticized [Liberatore and Funtowicz, 2003; van der Sluijs, 2005; McKinley et al., 2012]. Science produced under that model has political oversight and funding but minimal interference. The model views science as providing an independent accumulation of truths and tools that can be used, or “cherry-picked,” to inform policy. “Truth” has a different meaning for different people [Nordstrom, 2012]. The demarcation model has efficiently enabled the countering or mitigation of the potentially devastating effects of storms, floods, earthquakes, epidemics, and other hazards, at least in countries and places that wisely used the information.

Clear and accurate perceptions and predictions, politically imperative follow-ups, and unity of goals generally explain the successes that happen. Experiential learning is provided through relatively frequent, acutely felt, fast-unraveling disruptions. For many of the situations, the scientific information needed is clear, as are the consequent policies. Science provides crucial information and tools. On the policy side, managers *know*, through experience, what information they need, what they need to monitor and what steps need to be taken. Efficiency and effectiveness trump everything else because public feedback to poorly made policy decisions and actions can be fast and brutal. All sources of judgment align for the relatively immediate interest of the community.

When does the demarcation model fail? Figure 4 illustrates properties of systems and issues for which a demarcation model is less appropriate. More difficult, slower, processes may need to be applied with the

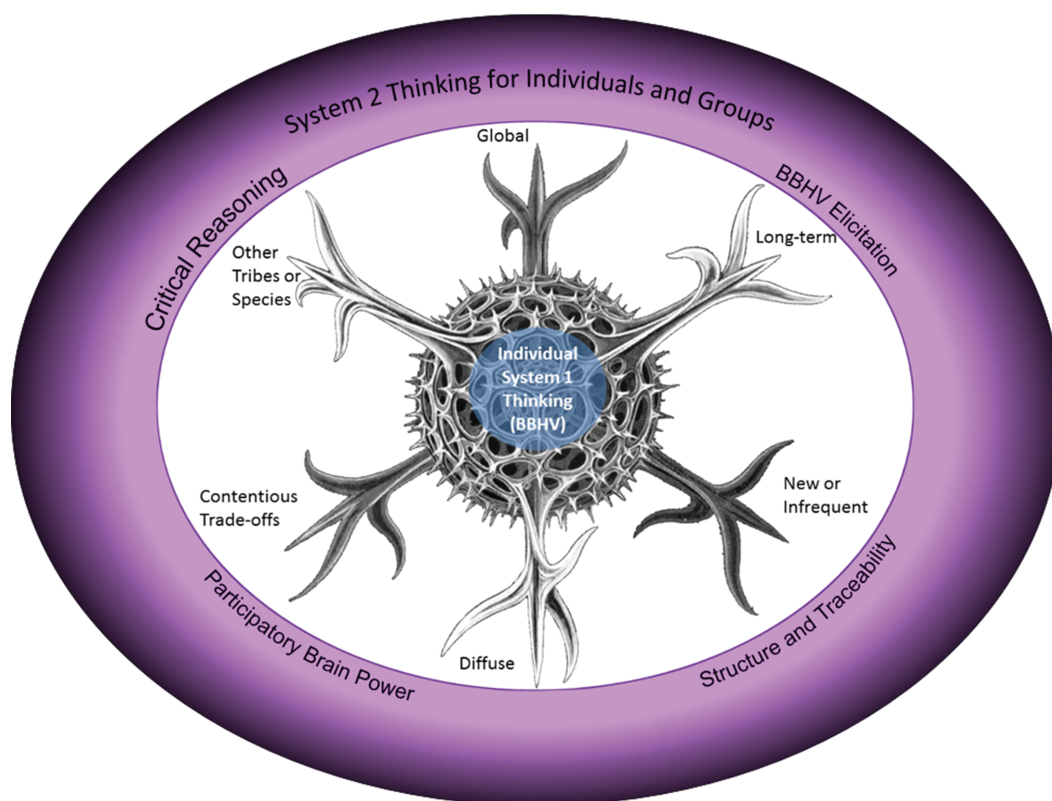


Figure 4. The structure of a radiolarian individual, *Haekel Spumellaria* [Haekel, 1904], illustrates two types of human and societal responses to a given situation or issue. One response (purple area) requires recognition of biases, beliefs, heuristics, and values (BBHV), critical reasoning (and S2 thinking for individuals and their groups), social participation, structure, and traceability, and slower, much more elaborate science and policy governance, such as that provided by our science-infused adaptive framework. Characteristics of issues or systems tending to need this response are shown next to the purple ellipse (e.g., global, long-term, diffuse). Opposite properties (e.g., local, short-term, acute) are not shown but would characterize systems and issues, at the center of the radiolarian, that would best be addressed with individual-based, innate, system 1 thinking, and the efficiencies provided by human BBHV.

more explicit critical reasoning and participatory characteristics used by our science-infused adaptive framework (cf. Figure 3).

Creeping normality, unanticipated problems. The demarcation model also does not work well in addressing issues in which (1) the public does not react to gradually increasing problems or changes until some threshold of perception is finally crossed, or (2) problems or disasters are unanticipated, or (3) group or political interests are involved and certain losses are at stake. We do not monitor or investigate what is not perceived as important until it becomes so. For example, the perceived value of collecting baseline water-quality data for groundwater and surface water in the U.S. increased greatly after public fears arose regarding the potential impact of unconventional oil and gas extraction activities on drinking water sources [Vidic *et al.*, 2013; Bowen *et al.*, 2015]. Similarly, the perceived value of paying attention to sediment deposits emplaced by historical and prehistorical tsunamis became greater in Japan after the experience of the 2011 Tōhoku earthquake and tsunami that caused the Fukushima Daichi nuclear disaster in Japan. Even though Japan has experienced many earthquakes and tsunami in the last 100 years, and has earlier records of such events, human perception of the possible chain of consequences initiated by the devastating earthquake and tsunami of March 11, 2011 was simply not there, or not fully realized, at least amongst the people who could have taken precautionary actions [Noggerath *et al.*, 2011; Lochbaum *et al.*, 2014]. As Stoler [2012] states:

Human beings create history on the basis not of reality but their perceptions of reality, perceptions that are often far removed from what actually occurred. But what actually occurred ... is visible only from the hindsight that the study of history presents.

We suggest that through a greater understanding of our sources of perception and judgment, and greater recognition of our BBHV, it is possible to recognize some of the potential blind spots, or negative space, of our constructs [Glynn, 2015; Voinov *et al.*, 2016]. What we then need is an inclusive participatory process (rather than a demarcation model) that engages a meaningful diversity of perspectives to test, communicate, and follow-up on those perceptions. Our science-infused adaptive framework meets these needs.

Single resource/issue assessments. The demarcation model is often successful in providing assessment of a single resource, for example, a mineral or energy resource. Scientists create an independent assessment using an explicit and transparent methodology. The methodology is reviewed and commented on by the stakeholder industry or interested agencies, and revised as appropriate by the scientists.

However, the demarcation model can sometimes fail, especially if there is substantial complexity in assessing the single resource or issue. The scientific methodology may be flawed, for example because it makes inaccurate assumptions, has too narrow a focus, does not consider future technological or resource change ... in other words, because of BBHV. In addition, power dynamics and manipulations may lead stakeholders or policy makers or scientific experts [Oreskes and Conway, 2010, 2013] to inappropriately cherry-pick, reorganize, or hide information provided. Information can be selectively revealed either to enhance the power or dominance of an individual or constituency, or to support preordained decisions; BBHV dominate in this case. Poincaré [1905] stated:

The Scientist must set in order. Science is built up with facts, as a house is with stones. But a collection of facts is no more a science than a heap of stones is a house.

Without appropriate, unified governance of both science and policy, without transparency, accountability, and the checks and balances potentially offered by more inclusive, more participatory processes, scientists, and policy makers have the freedom to selectively order and rearrange scientific facts to benefit personal or institutional goals rather than those of the wider community. As discussed earlier, having *a priori* core principles accompanied by Trust/Join processes is essential to our suggested framework [Voinov and Bousquet, 2010; Voinov *et al.*, 2016].

More complex systems and the difficulties of adaptive governance. Improved management of a resource or an issue can be obtained with the integrated help and proper governance of science and policy, and with processes described by our adaptive framework (Figure 3). The Lake Taupo case study (cf. Supporting Information), previously mentioned, demonstrates these processes. The case study shows that improved management is a complex activity that spans across politically long time scales. Other examples of beneficially interleaved, inclusive, transparent science and policy governance include a multiparty agreement for

water management for the Klamath Basin in Oregon (https://www.oregon.gov/owrd/pages/Klamath_Basin_Task_Force.aspx; <https://klamathrestoration.gov/>), and the development of a water-management plan for the Middle Rio Grande Basin in New Mexico [Cockerill *et al.*, 2006]. Generally, participatory planning works well if no specific constituency is overwhelmingly more powerful than the others [National Research Council, 2013], and if the coordinating entity is highly respected by all parties and considered credible. It also helps greatly if complexity and scales are relatively limited and well-defined (e.g., in time, space, and number of relevant processes, participants, and coordinating entities). When complexity and scales get greater, maintaining a structured, inclusive, transparent, and accountable process that makes recorded predictions and conducts meaningful follow-ups gets much more difficult and definitely much slower. For example, in contrast to the Klamath Basin example mentioned above, science and policy coordinators for the San Francisco Bay-Delta system have struggled to agree on a central plan to address, in the face of climate and land-use change, the competing issues of water allocation for different constituencies, for ecological needs, and for the management of the Endangered Species Act and Clean Water Act. Norgaard *et al.* [2009] have used the example of the Bay-Delta system to illustrate some of the problems faced by adaptive management frameworks for large complex systems that require long-term, highly contentious considerations in the face of short political time-scales with rapid turnover of personnel.

When complexity and trade-off decisions predominate, the demarcation model fails. The most difficult problems are those in which (1) trade-offs must be made between the extraction of various resources and the preservation of others or of environmental conditions, (2) there are multiple constituencies involved, and (3) one or more of those constituencies can express itself strongly and perceives an immediate loss from any policy decision or action. The demarcation model may be the easiest, most efficient model to follow if policies and actions can be imposed top-down; however, those policies may be less than optimal in representing and protecting all necessary interests. Our adaptive framework may offer a more optimal path, or at least one that (1) has structure, traceability, transparency, and accountability, solicits S2 thinking, and considers *science as a process*; and (2) seeks to recognize S1 thinking and BBHV while offering useful recorded predictions. This framework tries to identify winners and losers for multiple communities in the short- and long-term and seeks ex-post review or postaudits. Some agreement may even be reached for relatively small-scale fewer-issue systems trying to tackle multiple natural resources, species, and/or outcomes.

The critical reasoning and multiple perspectives needed to optimally address these types of systems are not always available though. Groupthink [Janis, 1972] can result, for example, when there is a strong constituency for a new paradigm or approach. In our view, this is seen in the area of valuing ecosystem services and in the consideration of “green infrastructure” benefits. Both paradigms offer promising new considerations of “Nature’s benefits to man” (BBHV example: man is an undefined entity that exists outside of nature with the aim to make use of it). However, in our view, the community and most individuals studying these promising paradigms have a strong tendency to ignore any possible disbenefits or negatives. The paradigms and their studies would be much more useful and credible if they were more critically evaluated, with full consideration given to both positives and negatives, and winners and losers of all sorts (present or future, local or not, human or not, acute or diffusely dispersed).

Long-term risks for the commons? Short-term benefits are key. Addressing long-term, unequally perceived, hazards to a broad community are also a challenge, especially when the short-term costs associated with possible solutions are more acutely felt than the longer-term benefits. Short-term perceptions and needs trump potential long-term benefits, which explains why it is difficult to find globally acceptable solutions to mitigate or reverse our effects on global climate change. Beliefs and groupthink rather than carefully analyzed information and predictions abound. Changing beliefs is extremely hard. Finding short-term credible benefits to long-term solutions seems the practical approach for getting buy-in. There is some evidence of this in developing long-term solutions for high-level nuclear waste disposal: some communities that have become habituated to and have been employed by nuclear power facilities are sometimes willing to have high-level nuclear waste sited near them. Again, this type of issue can sometimes be dealt with top-down, but the ensuing solutions and implementation of follow-ups are not likely to be optimal. Our adaptive framework (Figure 3) can be useful in eliciting BBHV recognition, in forcing explicit predictions and audits, and in discussing winners and losers. However, for a science/policy governance process to be

successful for this type of system or issue, stakeholders, and in some cases their descendants and other communities need to take on ownership of the problems and the solutions.

Successful science/policy governance is an ownership process. Successful governance is not just a pile of “truths” to be dealt with, or the following of a set of beliefs inculcated by evolutionary and cultural processes for problems/issues that are no longer those of today. Critical reasoning (S2 thinking) can be initiated by ownership of problems and solutions. Ownership starts small: with the local, the present, and the demonstrable [Voinov *et al.*, 2016]. Bottom-up participatory processes generally create much more ownership than top-down solutions. Bottom-up processes can also generate knowledge and progressively change cultural norms. They also have the potential of being scaled up through the use of novel Internet and communication technologies (ICTs), although trust is still hard to build and engender solely through ICT. ICT also offers unique opportunities to store the information and derived understanding resulting from the application of our cyclic framework. Although there would be limitations, accessible databases could be created of (1) case studies, (2) types of participants, (3) problem and solution characteristics, (4) predictions, uncertainties, and anticipated winners and losers, and (5) follow-up monitoring, results, and audits. Eventually, large-scale, long-term problems, and solutions may necessitate top-down controls or policies. However, even those cases could be better informed through the use of such databases.

6. Conclusions and Suggestions

We have been generally successful, as human beings, in facing the problems and issues that arose frequently and acutely during our adaptive past. These experiences have given us biases, beliefs, heuristics, and values (BBHV) that we often use very efficiently when confronted with problems and issues similar to those of the past. The type of thinking that we predominantly use to address these types of situations is called S1 thinking. BBHV, however, can get us into trouble when dealing with new or other types of situations, especially those that (1) involve a wider community, (2) are infrequent or more diffusely perceived, (3) take place over large spatiotemporal scales, and/or (4) necessitate transdisciplinary science and multiple perspectives to come up with optimal solutions. These types of situations require a more logical, serial, slow type of thinking, which is often called S2 thinking. This paper has:

1. Explored our human sources of judgments, decisions, and actions.
2. Discussed how those sources translate into different biases or BBHV that can negatively affect both the conduct of science and the development and implementation of policy. We have also mentioned techniques that can be used to recognize and possibly counter these BBHV.
3. Commented on the use of art and emotions that can help bring communities together, and also illustrate our common beliefs and biases.
4. Explained the progression between sensory observations, the acquisition of data, the structuring of information, and the internalization of knowledge, which in turn can serve as a basis for making judgments.
5. Presented a science-infused adaptive framework (Figure 3) that can provide a useful guide for thinking about science and policy governance for the creation of knowledge and the improved management of complex systems and issues. The framework solicits greater recognition of our BBHV, more inclusive participatory processes, explicit recorded descriptions and predictions of policy decisions and management actions and their expected consequences, and greater accountability through follow-ups, ex-post review and/or postaudits of those predictions.
6. Provided a typology of science and policy governance, and its successes, and failures when addressing different types of systems and issues, especially in the realm of natural resources, hazards, and the environment. We have also discussed when the traditional demarcation model of science and policy is relatively successful and when it is not.

The main message of our paper is simple. Structured processes, critical thinking, inclusive participation, avoidance of groupthink, transparency, accountability, and follow-up are hallmark principles of what is needed for science-infused governance and policy for many of the issues currently faced by society. In our view, it is paramount for science to engage in action [Voinov *et al.*, 2014, 2016]. Scientists need to engage with stakeholders and policy-makers and foster participatory processes in science and policy governance. This involves the definition of problems, the production of information and knowledge, the development

of predictions, the identification of possible solutions, and follow-up on decisions and actions taken. Recognition of the role of BBHV is essential for all steps of this process, and for everyone, including scientists.

Management and regulatory entities that claim to have a scientific basis for their decisions and actions ought to make accessible, documented, traceable predictions (as well-defined as possible and with appropriate uncertainties) of the expected consequences of their decisions and actions. To improve knowledge and management of complex systems, these entities also ought to monitor consequences of their decisions/actions, and be accountable through follow-up analyses, reviews, and postaudits of their predictions.

It is easy to find failures of science and policy management [Klein, 2007]; it is easy to miss or discount high-impact low-probability events [Taleb, 2007]; and it is easy to get discouraged with human or community behavior [Oreskes and Conway, 2010, 2013] in our need to more optimally and efficiently manage the complex systems that we are a part of.

We are encouraged, nevertheless, by the opportunities that new ICTs offer in improving governance of ourselves and our communities. Entire computer operating systems (e.g., Linux) and encyclopedias (e.g., Wikipedia) have been built through collective goodwill and participatory processes [Raymond, 2000]. Non-ICT older models of societal collaboration also exist (e.g., agricultural cooperatives: Goussault [1961, 1976]). The recent trend toward providing Open Access to data and models used by scientists is admirable because it allows greater transparency and possible reproducibility checks, and because it is an essential element of community-based science [Voinov *et al.*, 2008, 2010]. Why couldn't there be a similar "Open Traceable Accountable Policy" initiative that followed the science process outlined in our framework and that provided records through readily accessible databases? Although we recognize that special situations and restrictions would occur, we do not find any inherent problems with using an "Open Traceable Accountable Policy" to create long-term knowledge and to improve management of our complex systems. This would be especially appropriate for policies and actions that claim to be science-based.

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