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Ecological complexity, fuzzy logic, and holism in indigenous knowledge

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ABSTRACT

Some indigenous knowledge is said to be holistic in the way it deals with the environment. Given the difficulties of Western science with complex environmental problems, any insights from the holism of indigenous knowledge are of major interest. Based on examples from Inuit and other northern peoples, it appears that indigenous knowledge approaches complex systems by using simple prescriptions consistent with fuzzy logic. Specifically, indigenous knowledge pursues holism through the continued reading of the environment, collection of large amounts of information, and the construction of collective mental models that can adjust to new information. Such an approach serves the assessment of a large number of variables qualitatively, as opposed to focusing on a small number of variables quantitatively.

1. Introduction

It is said that indigenous knowledge is holistic, but not many studies have documented how this holistic approach works in practice. Exceptions include studies of Polynesian navigation by Turnbull [26] and Balinese irrigation by Lansing [13]. In dealing with ecosystems, the holism of indigenous knowledge is in the context of complexity. Ecosystems are nested systems (e.g., a small watershed inside a larger watershed and so on) and typically show variation in spatial and temporal scales, making them extremely difficult to predict and control [14]. Ecosystem management is a postnormal science, as Funtowicz and Ravetz might put it, a poor fit with conventional positivistic science that works best when systems are bounded and control is possible [8]. Western science-based societies have tended to simplify ecosystems to be able to manage them (e.g., agriculture) and dampen natural variability and renewal cycles – but at the cost of impairing the long-term health and resilience of ecosystems [11].

The knowledge and practices of indigenous societies are of significance in this context. Even though indigenous knowledge does not have the techniques and quantitative tools at the disposal of Western science, some systems of indigenous knowledge seem to have developed ways to deal with complexity. Any insights from indigenous wisdom in regard to ecosystems are of huge potential interest, given that modern society has not been particularly successful in managing ecosystems sustainably.

Diamond [7] and others have shown that many ancient societies did not live in harmony with their environment, and not all indigenous groups necessarily do so in the contemporary world. However, where traditional societies have co-existed with their ecosystems for a long time, there is strong evidence that this is not explainable solely in terms of low numbers of people and low-impact technology. The accumulation of evidence, especially in the last two decades or so, indicates that some indigenous groups have resource-use practices that suggest a sophisticated understanding of ecological relationships and dynamics [3]. Such practices tend to be backed up by worldviews that see human as part of the ecosystem, based on relationships of respect for the land and for living beings [2, Chapter 5].

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Further, there is evidence that indigenous resource-use practices can evolve over time by adaptive learning, based on the elaboration of a gradual understanding of the environment as well as on lessons learned from mistakes [4]. Geographic variations of such sophisticated management approaches are found, for example, in reef and lagoon tenure systems in Oceania [12]. Even though our understanding of indigenous ways of knowing and knowledge systems is still rudimentary, the picture that is beginning to come into focus indicates that some traditional societies have experience in reading environmental variables to deal with ecological complexity. But it is difficult to see how these indigenous approaches might work. How do they do it?

Gadgil and his colleagues suggested that the key might be the use of "rules of thumb", simple prescriptions based on a historical and ever-expanding cultural understanding of the environment. These rules are often backed up by religious belief, ritual, taboos and social conventions. In the area of what science would call biodiversity conservation, for example, there seems to be four "rules of thumb" used in various indigenous societies. These are (a) the total protection of certain selected habitats (e.g., sacred forests and other customary sanctuaries), (b) the total protection of certain species of animals or plants (e.g., taboo species), (c) prohibitions concerning vulnerable stages in the life history of certain species (e.g., hunting taboos in south India for fruit bats at daytime roosts), and (d) practices of monitoring of populations and their habitat [9].

Such prescriptions in the form of rules of thumb have the advantage of turning complex decisions into rules that can be remembered easily and enforced locally through social means. Traditional reef and lagoon tenure systems in Asia-Pacific, with their taboo areas, taboo species and ritually announced opening and closing dates for permissible harvests, operate under the same logic [12]. The First Salmon ceremony of many indigenous groups of the Pacific Northwest of North America may have functioned in a similar way. A ritual leader and his helpers would watch the salmon swimming up the river and presumably make a qualitative assessment of a sufficient number of mature fish (spawners) escaping upstream to perpetuate the population. Then the fishery would be declared open and the event marked by a ceremony [23]. It may be argued that such a system, led by an experienced leader, can produce results similar to one achieved by a biological management system with population models, counting fences, daily data management and harvest quota enforcement – but without the whole research infrastructure, quantitative data needs, and associated costs.

Rules of thumb that cut across complexity, as in reef and lagoon taboos, is one way to grasp how indigenous knowledge systems might deal with ecosystem complexity. Another is to think of local knowledge as fuzzy cognitive maps that are qualitative models of a system consisting of variables and the causal relationships between those variables [20]. A third and related approach is to use fuzzy expert systems. Mackinson developed a model that utilizes fuzzy logic to capture and integrate scientific and local knowledge in the form of heuristic rules to fish herring [15]. Similarly, looking at local and traditional knowledge systems in the Caribbean island state of Grenada, Grant and Berkes identified ten categories of knowledge that are important for finding and catching tunas and other large pelagic fish. Conceptualized as a decision-making rule structure, these 10 categories of information, along with the feedbacks among them, can be thought to constitute an expert system [10].

Hence fuzzy logic appears to be a good fit with indigenous knowledge, and an approach that may help understand, or provide insights, on the question of how local and indigenous knowledge systems may be dealing with complexity. Our emphasis in this article is not fuzzy cognitive maps or fuzzy expert systems but fuzzy logic as initially conceived by Zadeh [27,28]. The paper pursues the idea that indigenous knowledge is able to deal with ecosystems as complex adaptive systems by using simple prescriptions, consistent with fuzzy logic thinking.

First we explore the nature of indigenous knowledge, and the similarities and differences between such knowledge and science. Language-based qualitative nature of indigenous knowledge establishes parallels with fuzzy logic models. After covering some fuzzy logic basics, we discuss the idea that indigenous knowledge pursues holism by considering a large number of variables qualitatively, while Western science tends to concentrate on a small number of variables quantitatively. The examples and illustrations are from northern Canada, involving four northern indigenous groups, the Inuit, the Inuvialuit (western Canadian Arctic Inuit), the Cree, and the Dene. Northern Canada serves as a suitable 'laboratory' for this discussion because there is a great deal of material available, and because of our own interest in the area over three decades.

2. Nature of indigenous knowledge

Indigenous knowledge is a body of knowledge built up by a group of people through generations of living in close contact with nature. It is local knowledge held by indigenous peoples or local knowledge unique to a given society, including some non-indigenous ones. When the knowledge is of ecological nature (and not all traditional knowledge is) one may use the term, traditional ecological knowledge. The working definition we have used for this term is "a cumulative body of knowledge, practice and belief, evolving by adaptive processes and handed down through generations by cultural transmission" [2, p. 7].

Every society has its own understanding of how the natural world works, a repertoire of habits, skills, and styles from which members of a society construct their livelihoods. As a knowledge–practice–belief complex, indigenous knowledge includes an intimacy with local land, animals, and plants. It also includes institutions (rules and norms) about interacting with the environment, and it includes worldview, as the worldview shapes the way people make observations, make sense of their observations and learn. These levels of ecological knowledge may overlap, change over time, and interact with each other. For example, the worldview informs what new knowledge is legitimate and can be incorporated into resource-use practice, what social sanctions and taboos on hunting and farming practices may be used [3,4].

For the insiders, indigenous knowledge is often a way of life and a way of knowing. For Western analytical purposes, there is a distinction to be made between knowledge as process, as opposed to knowledge as the thing known, consistent with Gregory Bateson [1]. When Northern indigenous participants were asked to describe traditional knowledge, there was consensus on the following meanings that seem to include both the process of knowing and the knowledge itself: practical common sense; teachings and experience passed through generations; knowing the country; rooted in spiritual health; a way of life; an authority system of rules for resource use; respect; obligation to share; wisdom in using knowledge; using heart and head together [2].

There are both similarities and differences between indigenous knowledge and Western science. Both kinds of knowledge are ultimately based on observations of the environment, both provide a way of knowing based on these observations, and both emerge from the same intellectual process of creating order out of disorder. But there are also differences. Indigenous knowledge, as an integral part of culture, tends to have an explicit social context; science does not. Indigenous knowledge traditions have their own rules about processes of knowing, and these tend to be different from the rules of science regarding evidence, repeatability and quantification.

Highlighting the last point, not all kinds of Western scholarship use numbers, but quantification is certainly one of the hallmarks of modern science. In many indigenous knowledge systems, by contrast, quantification is not emphasized; often it is not even considered important or relevant. And we know this from personal experience, indigenous knowledge holders are often baffled by the preoccupation of scientists to count and measure everything. What they value is the understanding of the environment, how to read and interpret signals from the environment, and the relationships within it, including those involving humans [2].

With regard to quantification, one can take the position that indigenous knowledge and Western science are different; at the same time, one can also take the position that they are complementary. Arguably, quantitative vs. qualitative understanding of phenomena is a false dichotomy. Quantification complements qualitative understanding, and both kinds of understanding together are more powerful than each alone.

Holism is the key characteristic of indigenous knowledge for the purposes of the present article. The following example may serve as an illustration of holistic thinking. The Arctic region has been undergoing rapid environmental change in the past few decades. Northern indigenous observations of climate change and abnormalities in animals (which may be related to Arctic ecosystem contamination), once dismissed by scientists, are being taken seriously. Indigenous observers do not carry out chemical tests for pollutants or gather quantitative data. But their ways of observing and assessing environmental changes provides insights regarding indigenous holism.

O'Neil et al. worked with the Inuit of Hudson Bay region in northern Canada and documented how they made sense of the contaminants issue. Their major concern was the observation of abnormalities in many animals, focusing on seals. The diagnosis of a sick animal relied on many locally developed indicators. The Inuit knew which animals were sick or abnormal. They had a sense of what normal animals should look like, based on their collective experience over many years. They made reference to specific signs that indicated that an animal was not well and should not be eaten: animals with *manimiq* (lumps), discoloured bones, abnormal liver, bumps and blueish spots in the intestines, and skinny animals. The diagnosis did not rely only on anatomical observations and the quality of the meat; the Inuit also observed the behaviour of the animal, its feeding, swimming and response to predators, reading signs of wellness continuously and cumulatively. Interpretations of elders were given weight, presumably because the Inuit expected that experienced hunters would have a more finely developed sense about the state of health of an animal [19].

Indigenous knowledge holders accumulate such information as a result of many years of observations (analogous to extensive sampling), the sharing of knowledge with other hunters and fishers (data pooling), and forming a collective mental model of what healthy animals would look like. Their "data" on animal health and abnormalities are language-based, rather than numbers-based, and comparisons are performed on perceived ranks (e.g., fat, thin, very thin). How these data are characterized and used strongly depend on the terminology used.

The mental processes of "data collection", concept formation and retention, and mental model formation among indigenous people follow patterns consistent with the language used, as language shapes terms and concepts. For example, it is well known that the Inuit do not attach much value to numerical precision. They also do not often appear to make simple linear, cause-and-effect type connections, as often done in the Western science. Rather, they see environmental change and related observations as empirically connected. Systematic generalizations regarding cause–effect relationships are in general regarded negatively. According to the Inuit worldview, making simplifications and generalizations of complex phenomena is "childish" and without sense (without *ihuma*) [18].

We argue that holistic thinking among the Inuit is possible because precise categorizations and generalizations are avoided. If all the relationships embedded in a holistic term were to be specified, the whole idea would become unmanageably complex. There seems to be an inverse relationship between the complexity of a system and the degree of precision that can be used meaningfully to describe it. Zadeh [28, p. 28] calls this idea, the principle of incompatibility: "as the complexity of a system increases, our ability to make precise and yet significant statements about its behaviour diminishes until a threshold is reached beyond which precision and significance (or relevance) become almost mutually exclusive characteristics."

It is in this sense that precise quantitative analyses of the behaviour of complex systems are not likely to have much relevance to the real world. Some kinds of indigenous knowledge work because (a) there are large amounts of information; (b) it is collected continuously; and (c) changes are incorporated into the collective mental model as new information flows in. Herein lies the essential similarity of indigenous knowledge and fuzzy logic. The three points above are also the backbone of fuzzy logic models. In both cases, the analysis of the complex system behaviour is carried out, not by using numerically precise data, but by using language-based data that are qualitative and rich.

3. Fuzzy logic and indigenous knowledge

Fuzzy sets, a generalization of set theory, were developed as a way to represent the imprecise nature of information in everyday life. To use an illustration offered by Bezdec [5], suppose you are approaching a red light and you must advise a driving student when to apply the brakes. Would you say, ‘‘apply the brakes 25 m before the red light’’, or would you say, ‘‘Brake pretty soon’’? The latter of course, because the former instruction is too precise to be implemented. In most everyday situations, precision may be quite useless while vague directions, consistent with the imprecise nature of data, can be interpreted by the human brain and acted upon.

Practical applications of fuzzy logic (also referred to as fuzzy thinking, fuzzy models or fuzzy sets) in electrical and computer systems include self-monitoring and adjusting ‘‘smart’’ systems such as intelligent cars, subway trains (e.g., Sendai, Japan) that can detect and adjust to changing conditions, and your humble rice cooker with fuzzy logic technology. All ‘‘soft computing’’, including decision-support systems, Geographic Information Systems (GIS) and Geographic Positioning Systems (GPS) use fuzzy logic [29]. Applications are found in computer science and artificial intelligence, in fact, in almost all engineering fields [5].

Fuzzy logic is a mathematical approach for dealing with complex systems where only approximate information on components and connections are available. It is a way to deal with uncertainty and uses rules of thumb. It is suitable for concepts and systems that do not have sharply defined boundaries, or where the information is incomplete or unreliable. It is an unusual approach because it breaks with the yes–no binary tradition used in most science and computer applications.

Classical logic of precision, which forms the basis of Western science, was developed by the Greek philosophers, notably Aristotle, whose works gave rise to the so-called ‘‘laws of thought’’. One of these is the ‘‘law of the excluded middle’’ which forms the basis of later Cartesian logic. This law states that every proposition has to be either true or false. It is thought that the tendency of Western science to regard matters as either black or white stems from this bivalent yes–no logic and the Cartesian tradition based on it. Even during Aristotle’s time, there were some philosophers, Plato among them, who did not agree with the law of the excluded middle. Plato postulated that beyond true and false, there was a middle ground. One could say that if Cartesian science is based on Aristotle, the idea of fuzzy logic is based on Plato.

In fuzzy logic, things need not be precisely defined or quantified before they can be considered mathematically; fuzzy logic models do not need precise information inputs. Like the human mind, fuzzy logic puts together related objects into categories in such a way as to reduce the complexity of the processing task. Fuzzy logic provides the tools to classify information into broad categorizations or groupings, simulating the workings of the human mind. According to the founder of fuzzy logic, Zadeh [28, p. 28], ‘‘the premise is that the key elements of human thinking are not numbers, but labels of fuzzy sets, that is, classes of objects in which the transition from membership to non-membership is gradual rather than abrupt.’’

Zadeh’s approach has three main distinguishing features: use of linguistic variables in place of (or in addition to) numerical variables; characterization of simple relations between variables by fuzzy conditional statements; and characterization of complex relations by fuzzy algorithms. A linguistic variable is defined as a variable whose values are sentences. For example, if ‘‘fat, thin, very thin’’ are values for fatness, then fatness is a linguistic variable. Fuzzy conditional statements are expressions in the form ‘‘IF *a* THEN *b*.’’ A fuzzy algorithm is an ordered sequence of instructions, as in a recipe for chocolate fudge [28].

Fuzzy models rely on language-based information that is converted to simple mathematical expressions that can then be manipulated to make mathematical inferences. For the purposes of indigenous knowledge, we need not be concerned about the mathematics of fuzzy sets. The important consideration is language. To take the example of Inuit observations of ‘‘skinny seals’’ or ‘‘fat fish’’, fatness is the linguistic variable and the adjectives are linguistic values. Qualifying terms such as ‘‘and’’, ‘‘or’’, ‘‘not’’ are called linguistic connectives.

Using the example of Inuit observations of unhealthy seals, let us say that experienced hunters among the Inuit of Hudson Bay have been hunting large numbers of seals (a large sample size) and finding that many of them have abnormalities. Over several hunting seasons (continuous set of observations), hunters have noticed that some seals are thin, some have discoloured bones, and some have abnormal livers. After a while, the experienced hunters would begin to formulate an opinion about the general goodness of the seals to eat.

To put it in fuzzy model terms, the hunters observe seal fatness (variable 1) during the sampling. There is an existing mental model of the various values (different degrees of fatness/thinness) of this variable from experience and collective memory of experienced hunters and elders. Each seal is evaluated instantaneously against this model. The seals may be assessed to be generally thinner, and variable 1 is assigned a fatness/thinness value. In fuzzy models, it is assigned a certain weight between 1 and 10. Other variables such as discoloured bones (variable 2), condition of livers (variable 3), and so on, are assigned different weights, based on the existing mental model of a healthy seal that is good to eat.

All the relevant variables according to the model are weighted. IF variable *x* has a degree of thinness *a*, THEN the seals are assigned a fuzzy conditional statement. This type reasoning is used for all the variables specified, and helps evaluate the suitability of the seal for eating. In fuzzy models, several ‘‘IF a THEN b’’ type statements are used simultaneously and in a flexible way, changing the weightings as observations accumulate. Although we do not attempt this here, fuzzy models are able to quantify (by assigning numerical values or weights) the qualitative judgments of hunters based on their expertise.

Note that Inuit observations on the fatness/thinness of seals (and other variables) are not quantitative. For purposes of the kind of science that requires quantitative data to make conclusions, Inuit observations are difficult to use. Critics may dismiss them as anecdotal, or worse, irrelevant. Rather than requiring quantitative data, fuzzy logic is able to work with the approximate values assigned to the categorizations of fatness/thinness that can be inferred from the language used by the hunters. Using weightings and mental models of Inuit experts, and then assigning numerical values to these, fuzzy logic simulates human judgment in making sense of a large number of variables.

4. Making sense of indigenous knowledge as fuzzy logic

The illustration of fuzzy logic using the case of Inuit indigenous knowledge of seal wellness, stops short of addressing one key question: what is the advantage of valuing Inuit knowledge in such a case, if quantitative scientific data can be obtained instead? The short answer is that both kinds of knowledge are desirable because they extend the range of information available. The long answer is, the two kinds of knowledge have different relative strengths and a potential for complementarity. Indigenous knowledge appears to bring some unique advantages in dealing with multiple variables and complexity.

In this section, we illustrate this point, first by further pursuing the example of Arctic contaminants, and extending the seal wellness case. Second, we use the example of Inuvialuit observations of climate change in the western Canadian Arctic to make the point that the ability of indigenous knowledge to deal with many variables is valid for different kinds of environmental knowledge. The example also illustrates that indigenous knowledge complements science with scale-specific information.

Based on the available literature, Donald Cobb and colleagues compiled a comprehensive table of environmental quality indicators used in the study of contaminant-related effects in fish and marine mammals, one column for indicators used by scientists (toxicologists), another column for indicators used by northern indigenous knowledge holders. The two sets of indicators, as used by the two knowledge systems, assess environmental conditions and wellness in their own way [6].

The science of toxicology uses many indicators at the chemical, biochemical and cellular levels. At these levels, indigenous knowledge is generally not very useful, except that some northern indigenous people are apparently able to taste and smell some contaminants, or effects of contaminants, in animal tissues. However, at the levels of the whole organism, population and community, local observations and indigenous knowledge seem to provide a range of indicators comparable to science. Some toxicological effects, such as physiological changes, are not observable to hunters. However, such physiological effects may express themselves as behavioural effects, and the Inuit are experts on reading animal behaviours. The review found some indicators that may be noted by indigenous observers and not normally studied by science. These include the detailed observations of different kinds of fat on the body of an animal that are used as indicators of health [6].

A major difference between science and indigenous knowledge is that toxicological studies tend to work with a single analytical tool at a time, focusing on one or a small number of indicators. By contrast, indigenous knowledge focuses on a large number of less specific (and probably multicausal) indicators used simultaneously as a suite. Whereas scientific approaches seek indicator specificity and result in quantitative studies of a small number of indicators, those based on indigenous knowledge do not produce formalized generalizations. But the use of a broad suite of simpler indicators (instead of a few detailed and costly ones) gives the hunting community feedback on many aspects of environmental health, a holistic picture of the environment. The use of a broad suite of simple indicators provides built-in adaptability in a fuzzy logic sense. That is, such community-based indicators could be readily modified with changing conditions, providing flexibility in the collective mental models used and interpretations made.

The Inuit Observations of Climate Change study further illustrates the ability of indigenous knowledge to deal with multiple variables and complexity, and shows that local observations can provide information at the appropriate spatial scale to complement science [22].

Most scientific studies of climate change use models to generate projections at the global and regional levels. Scientific field studies on climate change typically provide discipline-specific results, based for example on climatic variables (temperature, precipitation, etc.) or based on plants (distributions, changes in treeline) or based on different groups of animals (changes in food and physiology, migration patterns, etc.). By contrast, the Inuvialuit offer a full range of observations on all aspects of climate change, similar to the broad suite of simple indicators in the Arctic contaminants case.

As summarized by Mark Nuttall and colleagues, the Inuvialuit of one small Arctic community, Sachs Harbour, are able to provide some 25 kinds of evidence of climate change, spanning the areas of physical environmental change; predictability of the environment; travel safety; access to resources; and changes in animal distributions and condition. In the area of physical environmental change, for example, Sachs Harbour Inuvialuit noted the reduction of sea-ice cover and lack of multiyear ice around the community in summer, and the thawing of permafrost. All of these changes made environmental predictability, travel safety and resource access more difficult. Hunters rely on their ability to predict the weather and the timing of animal movements, and to read snow and ice conditions (“is the ice firm and safe to travel?”). Increased ice movements in winter and spring, changes in the distribution of leads, cracks and pressure ridges, as well as overall thinning of the ice, have all affected access to resources [17].

The collective mental models of the Inuvialuit are very exacting in combining the variables they consider relevant. For example, sea-ice observations are evaluated jointly with changes in wind frequency and strength. Weather instrumentation, along with remote sensing, provides precise information on each of these variables but not on the *combination* of these variables [16]. Whereas global models produce results based on average change, the Inuvialuit consider numerically precise "average change" as more or less irrelevant, and focus instead on the magnitude and frequency of extreme weather events, variability, and predictability [17].

Complex systems phenomena, such as climate change, occur at multiple levels, and there is no one correct level of analysis. The system must be analyzed simultaneously across geographic scale, from the global to the local. But the relative emphasis of science has been at the global level. The fact that indigenous knowledge provides local-level understanding is particularly important because it complements science precisely at the level where information is poor.

5. Prospects for indigenous knowledge

"Not everything that counts can be counted, and not everything that can be counted, counts" (Albert Einstein)

We started by asking how indigenous knowledge develops holistic approaches, and focused on fuzzy logic as a way to explain how rules of thumb and other simple prescriptions can be used to deal with complexity. It is well known in the theory of complex adaptive systems that complexity can emerge from simple rules [14]; conversely, it seems, simple rules are appropriate for dealing with complex adaptive systems. How does it work? Indigenous knowledge seems to build holistic pictures of the environment by considering a large number of variables qualitatively, while science tends to concentrate on a small number of variables quantitatively. It is a tradeoff captured in Zadeh's [28] principle which says that an inverse relationship exists between the complexity of a system and the degree of precision that can be used meaningfully to describe it.

It should be qualified that not all kinds of indigenous knowledge are holistic, and obviously not all Western science is reductionistic. Some (but not all) kinds of ecology, systems science, gestalt psychology, quantum physics and fuzzy logic are examples of holistic areas within the predominantly reductionistic tradition of Western science. The dominant tradition, captured in the "normal science" terminology of Funtowicz and Ravetz, is appropriate for relatively simple, controllable systems [8]. By contrast, there is a large degree of uncertainty in complex adaptive systems in which "not everything that counts can be counted". This limits the ability to make precise (and yet significant) statements about system behaviour. Complex adaptive systems cannot be readily comprehended by the use of conventional science – simply because we would be overwhelmed by data and not even be sure that the data are meaningful. Zadeh's insight was to recognize the nature of this problem and depart from precision, ironic for an engineer. In the process, his theories were apparently not well received by some major US corporations but embraced by some Japanese companies that ran with them. The rest is soft computing history.

Our analysis suggests that Zadeh's solution is a good fit with indigenous knowledge and its holistic treatment of ecosystem complexity, with the use of rules of thumb and broad suites of simple indicators, as in the Arctic contaminants case. The science of environmental toxicology is well developed, but there is an increasing recognition that the use of a few indicators, no matter how well chosen, may be inadequate in capturing complexity [6]. The indigenous solution is brilliant in building a holistic understanding by monitoring a large number of indicators over a long period of time, accumulating and accessing a large amount of qualitative data, and building a collective mental model of what healthy animals and environment ought to look like. Even in a highly analytical science such as toxicology, one can see the potential contribution of qualitative understanding provided by indigenous knowledge.

Similarly in the area of climate change, Inuvialuit observations cannot replace scientific measurements and models. But they can contribute to the overall understanding of the system, complementing science by filling in the otherwise missing local scale, providing baseline information, helping formulate research questions and hypotheses, providing insights regarding impacts and adaptation, and supplying community-based monitoring [22]. The crucial part of developing indigenous understanding was the ability to assess the veracity of change, based on their mental model of the predictability of the environment, the range of expected variation, and the expected frequency and severity of extreme weather events. On all three counts, the expected environmental variability in the collective mental model was exceeded in the 1990s and onwards [16,17,22].

Based on our analysis, indigenous knowledge can be analyzed as fuzzy logic and quantified with fuzzy sets, if it were desirable to do so. We do not attempt to do that here, in part because we are concerned that to do so will take indigenous knowledge out of its cultural context and add a level of analysis that is not appropriate. In any case, even without the quantification into fuzzy sets, holistic insights of indigenous knowledge are being recognized from northern Canada to southern India in environmental assessment and other fields [21]. The challenge is to find appropriate ways of bridging Western science and indigenous knowledge without absorbing the diversity of knowledge traditions into one dominant science [2,21,25].

Indigenous knowledge is a challenge to the positivist–reductionist paradigm [2] and to the essential question of what constitutes knowledge [25]. David Turnbull has argued that when local knowledge is probed deeply, "in no case does it come out looking like the standard Western notion of information;" rather, it tends to be a "blend of knowledge, practice, trusted authority, spiritual values, and local social and cultural organization: a knowledge space" [25, p. 560]. It is a lesson for futures studies that the ancient wisdom of indigenous peoples is such a good fit with fuzzy logic, a very new science – sometimes you have to go back to go forward [3]. The holistic approach is the key.

The basic idea is captured by Bateson who has criticized Cartesian science for creating false dualities such as the split between mind and nature (or nature and culture). Bateson observed that "The continuum of nature is constantly broken down into a discontinuum of variables in the act of description" [1, p. 165]. The conventional scientific solution has been to quantify a few of the variables, whereas the solution in indigenous knowledge has been to find ways of perceiving that continuum of nature and working with it. For Westerners, holistic Western sciences such as fuzzy logic help comprehend the concept. Indigenous knowledge holders do not need fuzzy logic to understand holism; they already practice it.

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