Article

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Matching Traditional and Scientific Observations to Detect Environmental Change: A Discussion on Arctic Terrestrial Ecosystems

Recent environmental changes are having, and are expected to continue to have, significant impacts in the Arctic as elsewhere in the world. Detecting those changes and determining the mechanisms that cause them are far from trivial problems. The use of multiple methods of observation can increase confidence in individual observations, broaden the scope of information available about environmental change, and contribute to insights concerning mechanisms of change. In this paper, we examine the ways that using traditional ecological knowledge (TEK) together with scientific observations can achieve these objectives. A review of TEK observations in comparison with scientific observations demonstrates the promise of this approach, while also revealing several challenges to putting it into practice on a large scale. Further efforts are suggested, particularly in undertaking collaborative projects designed to produce parallel observations that can be readily compared and analyzed in greater detail than is possible in an opportunistic sample.

INTRODUCTION

The Arctic regions are one of the planet's last wilderness areas (1, 2). Indigenous and other Arctic peoples who inhabit the Arctic depend on the services of unique marine and terrestrial ecosystems that have evolved to withstand harsh environments (3). The Arctic is also intimately linked to other parts of the planet. Biological and nonbiological resources are exploited for use outside the region and many birds, sea mammals, and people migrate between the Arctic and warmer regions. In addition, processes of heat and gas exchange occur at sea and on land in the Arctic that affect the climate system of other regions.

The climate, people, and ecosystems of the Arctic have been changing since at least the early Holocene, some 10 000 years ago. However, we have recently entered into a period of rapid and substantial environmental changes that are unprecedented in the Holocene and which are beyond the "memories" of people and ecosystems alike (4). These changes are often amplified in the Arctic and include greenhouse gas-induced climatic change, increases in habitat fragmentation by local human activities, increases in types and concentrations of contaminants originating outside the Arctic, changes in society and biodiversity, and increases in UV-B radiation because of decreases in stratospheric ozone.

There is a major need to detect and predict changes in environment and ecosystems of the Arctic, and to unravel the causes of change, in order to develop adaptation and mitigation strategies to prevent damaging changes or reduce their impacts. The task of detection, prediction, and attribution of causes of change is far from trivial. Many conventional scientific methods are being applied, but all have weaknesses and uncertainties despite their particular strengths. It is becoming clear that applying different methods to understand the same problem can reduce uncertainty, and there is an increasing need and urgency to include and develop appropriate additional methods. Furthermore, conventional scientific methods cannot be applied widely due to practical, logistical constraints. Gathering information from other sources can both broaden and strengthen our awareness and understanding of environmental change.

Traditional ecological knowledge (TEK) has been increasingly used in environmental research. TEK offers a great deal of valuable information, at least some of which can be documented and shared for the benefit of society at large and of scientific research in particular (5–8); and the perspective offered by TEK provides a useful complement to mainstream and scientific perspectives, particularly through emphasizing a holistic approach that includes humans and culture (9–12). Both approaches have been documented in many studies, with considerable evidence to support the basic claim that TEK and its holders are a valuable resource in modern environmental science.

In this paper, we argue that the use of TEK and science together has not realized its potential. One largely untapped area is the careful comparison of specific observations from TEK with those from science. Traditional and scientific observations are independent sources of information that can be brought together to increase confidence and depth of knowledge. While both methods have uncertainties of their own, overall uncertainty can be reduced when the methods are combined. The purpose of such comparison is not to "validate" one set of observations in terms of the other. Rather, it is to combine them while taking advantage of their differences in order to *i)* gauge confidence in individual conclusions; *ii)* identify new ideas for further investigation; *iii)* compare information gathered at different spatial and temporal scales; and *iv)* examine potential mechanisms to explain both sets of observations. We use TEK of terrestrial ecosystem change in the North American Arctic and results of conventional science investigations to demonstrate these ideas and the way they increase our understanding of current environmental changes and their impacts.

DEFINITIONS AND CONCEPTS

The scientific approach is well known, and traditional ecological knowledge is increasingly well recognized. That said, both incorporate and at times conflate a large array of methods, approaches, world views, and purposes. We therefore begin by reviewing both concepts and defining what we mean by them for the purposes of this paper.

There are many similarities between TEK and science, including an emphasis on replicability. Science attempts to produce results that can be achieved again by different observers, establishing a general rather than a personal principle. TEK allows people to survive and thrive by knowing what to expect, good or bad, and how to prepare for it. Both are based on observations and analysis, science through an explicit and formal process, and TEK through an implicit and flexible process. TEK and science also show complementarities. Science, for example, strives for generalizations in space and time whereas TEK provides observations based on long-term experience for specific localities. TEK relies on information from elders to deal with unusual phenomena, whereas science often resorts to old publications outside the scientific literature or experimentally simulates extreme events. There are, of course, differences as well in terms of methods, focus, and purpose. For this paper, however, we are concerned with observations of environmental phenomena, an area where both approaches have a great deal to offer.

Traditional Ecological Knowledge

A host of terms are used as synonyms or near-synonyms to "traditional ecological knowledge." These include indigenous knowledge, traditional knowledge and wisdom, local and traditional knowledge, and various combinations of these and other words. None is entirely satisfactory. We use "traditional ecological knowledge" and its abbreviation TEK simply because their use is widespread, and because they are not restricted to indigenous peoples alone. Similarly, there are many definitions of what constitutes TEK, referring to how it is generated, how it is transmitted, contrasting it with scientific knowledge, and so on. We use it to refer broadly to knowledge gathered and maintained by groups of people, based on intimate experience with their environment (9, 13). Methods for documenting TEK include key-informant interviews, community surveys, and group workshops (14).

While TEK encompasses a plurality of types of knowledge and ways that such knowledge is generated and perpetuated, three general characteristics are relevant to the purposes of this paper. First, TEK often emphasizes unusual events or conditions. These may be of particular relevance for safety, for example the possibility of dangerous ice conditions that may be rare but have serious consequences when they do occur. Second, the assessment of uncertainty, so important in scientific studies, is not explicitly addressed within TEK, and it is often difficult or impossible to gauge uncertainty when documenting TEK. Thus, while the likelihood of certain connections or associations may be described quantitatively in scientific reports, it is typically impossible to make an assessment of the uncertainty accompanying specific TEK observations. Third, TEK is typically local in spatial scale but may cover many decades and draw on knowledge handed down for many generations, in contrast to many scientific observations, which are typically intended to produce conclusions that are applicable across broader areas but which usually lack time depth greater than a decade or two at most.

In this paper, "TEK observations" refers to observations people make through their daily engagement with the environment, often through livelihood activities such as hunting, fishing, herding, and gathering. Instrumentation as seen in science is not often used, but local language and terminology are important tools as TEK observations are collected and shared through conversations, stories, and oral histories. TEK approaches to observing and assessing terrestrial ecosystem changes include:

- long-time observations at specific locations (for example, observations of animal populations at a particular hunting area or camp, or vegetation conditions at usual berry-picking locations from year to year);
- long-time observations over regular travel routes (for example, observations of nesting grounds located along travel routes, nature of the terrain, depth and condition of snow cover, ease of travel through scrub and forest, etc.);
- assessments of animal health based on observations of behavior and/or skinning and butchering (for example, the amount of fat can be assessed in terms of that year's climate/environmental conditions and compared to previous years);
- consultation among hunters and others on an individual basis, and more formally at community organizational meetings where observations of environmental conditions are compared and information shared;
- calling upon elders and other knowledgeable persons to advise in the case of unusual conditions or how to deal with their impacts (for example, changes in animal populations or migrations, poor water resources, etc.).

Reindeer in a snowfield in northern Sweden. Photo: P.Rosén

These are only some of the TEK approaches to understanding patterns, processes and changes in the environment. These approaches are fluid, always adapting to the circumstances and needs of the observer. Determining reliability or credibility is typically a matter of assessing the credibility of the individual making the observation. This assessment is usually based on factors such as the life experience of the individual and his or her reputation for holding sound knowledge about the topic. Members of the observer's own community are typically in the best position to evaluate these factors, although such an evaluation is implicit. Review of documented observations by community members is an essential element in establishing the reliability of a TEK study.

Scientific Ecological Knowledge

Discussions of the meaning of "science" are, if anything, more extensive than those about TEK (15). We use "scientific observations" to refer to observations made in the context of consciously controlled studies proceeding in a systematic fashion, often using complex instrumentation. Their main aims are to record, understand, and predict the states of systems and their dynamics. Scientific observations in ecology differ from TEK in that they usually have a strong numerical component and attempt to quantify the variability (that is one part of the uncertainty) associated with the observation. For terrestrial ecosystem change, the relevant approaches include:

– real time, field-based observations over time and space (for example monitoring populations of an animal, or monitoring the abundance of a rare plant);
– remote sensing (for example assessing the distribution of, and large-scale changes in vegetation);
– retrospective analyses of biological and other material (for example, determining the past performance of forests from tree rings and past assemblages of plants and animals from lake sediments);
– experimental manipulation of environment (for example when single environmental factors such as temperature and atmospheric CO^2 are controlled independently and in combination to *i)* understand the relative importance of various individual and interacting controls on the biological system; and *ii)* simulate future and past environments);
– experimental manipulation of biodiversity (for example when species are removed from an ecosystem to identify their role in ecosystem processes or when species are introduced beyond their distribution ranges to assess the potential for ecosystems to change in future climates);
– mathematical modeling (for example the synthesis of process-based knowledge from experiments and observations in order to predict general outcomes of changes in states of ecosystems, etc. over wider geographical areas and/or longer time scales than represented in the experiments and observations).

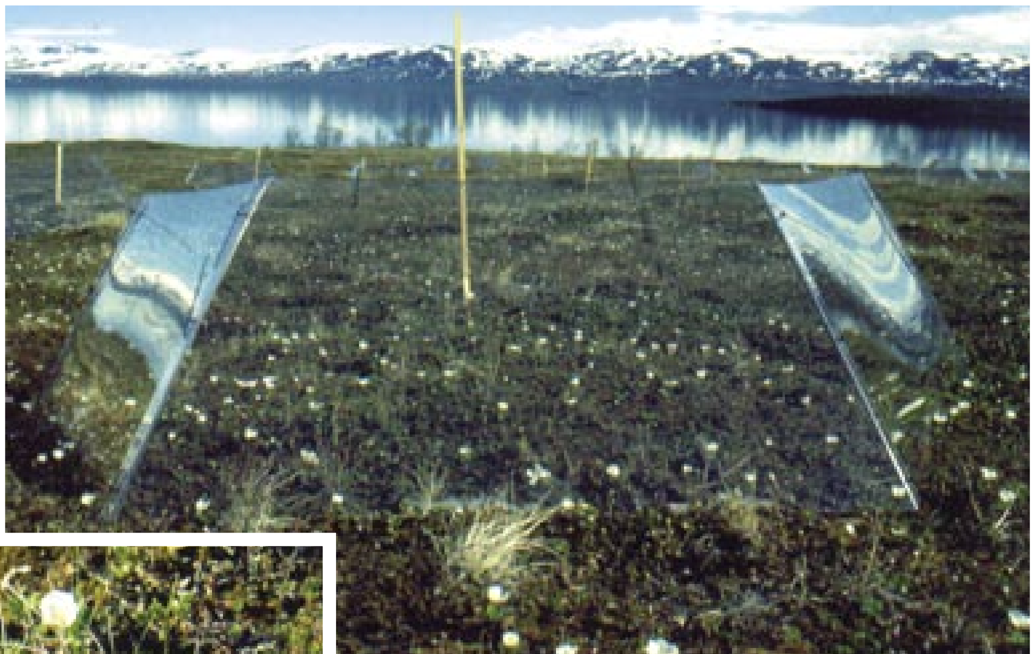
Each method has specific uses, but combinations of complementary methods are often used and the application of different methods to a particular problem reduces the overall uncertainties. While scientific observations have dominated our understanding of the natural system, each scientific method has uncertainties and limitations (16) and there is a constant need to improve our tools for understanding the present and predicted changes to our environment.

Scientists, in comparing results and contributing to the development of knowledge generally, engage in a rigorous process of review and comparison. Unlike the case with TEK, the reviews and comparisons are intended to remove the status of the individual, and to focus instead on the results. Thus, peer review and comparison with previous results are intended to be impersonal and unbiased. While not perfect, this system is explicit, and papers published in peer-reviewed journals can be taken to have met scientific standards.

ADVANTAGES AND CHALLENGES OF COMPARING OBSERVATIONS

Although a variety of approaches have been used to document or generate both sets of observations, each observation itself describes some aspect of the environment, which in turn can be compared with other observations made by other means. Our intent is thus not just to assess the utility of different methods, but to compare and combine the specific results to gain wider insights. Because each study has reported different levels and types of details (for example, annual averages *versus* seasonal distribution of precipitation, or changes in tundra plants generally *versus* species-by-species changes), we have tried to make comparisons and contrasts at similar levels of generalization or specificity, as supported by the available information. In some cases, this approach leads to very general comparisons, but this is preferable to possibly spurious comparisons based on overinterpretation.

For a number of reasons, the comparisons have turned out to be more difficult to make than was assumed at the outset. First, the TEK is usually gained for a specific locality and for specific years whereas the scientific understanding is usually gained from observations or experiments carried out elsewhere. Where the comparisons agree, there could still be flaws with either method because of local factors. For example, there might be evidence from warming experiments that flowering will increase and dwarf shrubs will grow higher. However, if the increased flowering and growth has been observed along drainage channels where there is nutrient enrichment, the apparent concurrence of results is spurious. Similarly, where the comparisons disagree, local factors could provide the explanation. For example, apparent disagreements between observations of lichen abundance may reflect that the TEK observations and scientific experiments were carried out on different vegetation types. Solving this particular problem is not trivial, but the comparison is still valuable. The comparisons per se focus researchers on areas of support and disagreement for further study while providing a general context of understanding for both groups.



Flowering Rubus chamaemorus in a blanket bog and experimental set-up of a warming experiment in Abisko, northern Sweden. Photos: H. Cornelissen.

Second, there are too few specific details of location and time of records together with magnitude of change (increased height of trees over a particular period, number of new mainland duck individuals per year, etc.) from TEK on the one hand, while appropriate comparative information from scientific research can

Table 1. Examples that suggest agreement between TEK and conventional science on terrestrial ecosystem changes. Note that the first two address detection of trends, and the third is evidence of a new phenomenon.

TEK Observation	Science interpretation	Comments	Recommendation
Willows, alders, and shrubs are more abundant in central Nunavut and in northwestern Alaska (21–23)	Myneni et al. (24) show increased NDVI in central and southern Nunavut. Experiments (25) and observations in Alaska (26, 27) indicate greater shrubiness during warming	Both the TEK and scientific observations are consistent over large areas.	Establish a monitoring program to quantify baseline information and compare growth trends with climate, nutrient availability, etc.
At Sachs Harbour, Northwest Territories, grass remains longer into the autumn and results in freezing damage (28)	Increased nutrients (29) expected during warming and increased CO2 and UV-B (30) suggest that longer leaf duration and increased frost damage could result from environmental change.	The science interpretations offer explanatory mechanisms that appear to support the TEK but actual mechanisms may differ at the TEK site.	Explore the mechanisms behind the TEK observations
New insects are seen at Baker Lake (31) and the Bering Strait area (32)	Insects with southern distributions are found north of their normal survival limits (33) and some butterflies are extending further north in Finland (34) and elsewhere (35)	At Abisko, one species of fly new to knowledge has been found (36), however, there are few scientific experts who can detect this	A two-way communication should record all sightings of new species for the region and globally. Presence or absence of data records should be confirmed

Table 2. An example that suggests disagreement between TEK and conventional science on terrestrial ecosystem changes.

TEK Observation	Science interpretation	Comments	Recommendation
In areas of Nunavut, there are more lichens now (21, 22)	A meta-analysis of warming experiments (37) and field observations show that lichens decrease during warming in areas of closed vegetation	More information from the TEK is needed to determine if the observations are a) in an area of warming, b) in an area of increased reindeer populations c) in an area of open vegetation	TEK and conventional science could work together to a) refine the predictions from the experiments and b) to explain the mechanisms behind the TEK observations

Table 3. Examples of TEK on terrestrial ecosystem changes for which conventional science data are apparently lacking.

TEK Observation	Science interpretation	Comments	Recommendation
Increased insect harassment of caribou near Baker Lake region in Nunavut (31)	Data currently absent or unavailable	The point agrees with anecdotal evidence and is what would be expected during warming.	Quantified observations should be initiated in different years/ climatic regions.
There is an earlier start of caribou migrations in the Kitikmeot Region of Nunavut, near Bathurst Inlet (21, 22)	Data currently absent or unavailable	Conventional science data are presumably available somewhere.	Conventional data needs to be found and standardized observations initiated.

often be buried in obscure reports on the other, whereas the accessible literature contains more generalized conclusions. Improved data availability is required on both sides.

Third, TEK observers and scientists often approach the same problem from different angles and examine different indicators. For example, TEK records cloudberry (*Rubus chamaemorus*) damage due to warm springs and summers, approaching the problem from one of berry consumption (17). In contrast, scientists have recorded flower production in response to experimental increases in spring and summer temperatures (18). One group is interested in food quality and availability, the other in ecological processes such as reproductive output. Simple communication between groups could lead both groups to exchange complementary information and record new data of relevance to the other.

Finally, there is the question of credibility of information from either source. For scientific results, peer review is the usual standard of credibility. In most cases, this is a satisfactory standard. For TEK, as noted earlier, community review can serve a similar function. That said, not all observations are necessarily acceptable at face value. A TEK report of increased UV-B, for example, would be hard to accept because the human eye cannot detect light of that wavelength. Such observations may be explained by the conflation of the actual UV-B light with some of its impacts, by publicity surrounding scientific findings that becomes accepted knowledge in a local community, or by other factors. While UV-B may indeed be increasing, TEK reports of the phenomenon cannot be regarded as an independent observation without more information about how that conclusion was drawn. Similar concerns must be applied to scientific observations and assertions. For example, indigenous people sometimes reject scientific findings that appear to be at odds with local knowledge and experience. In many instances, this rejection has turned out to be fully justified (19).

ASSESSING ENVIRONMENTAL CHANGE

We examined several studies of TEK, which recorded many separate observations concerning terrestrial ecosystems in the North American Arctic (20). These observations address plant and animal distribution, abundance, and performance; the behavior of specific animals; and the interactions among species and their environment (see "Detecting Trends" below). The observations also address the identification of new phenomena, such as the presence of new species, or a new relationship between species (see "Detecting New Phenomena" below). Information from a wide range of scientific studies was used as a basis for comparison. The results of the comparison can be placed in three categories: agreement (Table 1), disagreement (Table 2), and no corresponding observations (Table 3).

In cases where the scientific and indigenous observations agree, confidence in the observations is increased. Furthermore, there may be some insights into mechanisms (see "Examining Mechanisms of Change" below). In cases where the observations are in conflict, further evaluation may suggest reasons why one or the other is flawed, or may indicate that different mechanisms are involved in the two assessments and thus further study is needed to resolve the apparent conflict. In some cases, there simply is not a corresponding observation from one source for material drawn from the other. This may indicate a gap in documented information, or it may reveal information that is new from one perspective or the other; in either case, further research and observation are implied.

Several new insights emerge from the comparisons and from the review of documented TEK. There is compelling evidence from the TEK of changes in plant growth—particularly general references to increased or poor growth of vegetation—and changes in the populations of many birds, and some insects.

It has been found difficult to compare these observations with scientific data. Perhaps the records do not exist; perhaps they are buried in obscure reports; and, most probably, perhaps they exist in databases but have not yet been analyzed or published. Clearly Arctic peoples constitute a much larger population of observers—and year-round observers—than scientists. Further work should extend the initial efforts reported here. The changes in species performance and distribution noted by TEK should be integrated with the context of scientific records, areas of concern for biodiversity highlighted, and causes established.

Detecting Trends

One of the chief challenges in assessing environmental change is that of distinguishing trends from underlying variability. The detection of trends is a process of interpretation, involving information from more than one observation. Science and TEK may independently observe the same or similar phenomenon, which would increase confidence that any identified trends were not the result of uncertainty associated with either endpoint. Or, TEK and science may observe different phenomena, changes in which can best be explained by a single underlying cause. This is perhaps more typically the case, with one placing greater emphasis on a particular phenomenon than the other. For example, TEK may pay particular attention to the impacts of insect harassment of caribou (*Rangifer tarandus*) or the importance of the berry quality, neither of which may be assessed in detail by scientists. Changes in phenomena of this kind may be consistent with the expectations scientists have for a warming climate, evidence for which may be available from other sources. In this case, independent observations of different phenomena may both support the same causal hypothesis.

Another challenge in identifying trends is to select an appropriate baseline. Science changes over time, and few observations are made consistently over long periods. Because so much information is generated, much of it is effectively unavailable because it is not accessible at most libraries or *via* the Internet. Instead, it is stored at the institute where it was generated or appears only in obscure publications which have passed from the knowledge of most working scientists. As a result, many scientists may unwittingly measure trends across their own careers, but not over longer periods, and thus the baseline may be constantly moving (38, 39). This problem also exists in TEK, where standards for comparison may not exist. For example, observations of the sky changing color over time are difficult to assess for lack of such a standard. Similarly, observations of numbers of animals or of the expected timing of certain events may be based on personal rather than intergenerational experience. As with other difficulties in detecting trends, the uncertainties stemming from these problems can be to some extent overcome by the presence of independent observations of the same phenomenon or of phenomenon responding to the same cause.

Detecting New Phenomena

New phenomena seem, on one hand, to be more readily recognizable than changes in existing phenomena. On the other hand, it is often difficult to be certain that the phenomenon is in fact new, as opposed to being one that has simply not been noticed before (or not for a long time). For example, is the first recorded sighting of a bird in a given area evidence that its distribution has changed, or is it the result of greater effort, expertise, or care in observation? If the "new" bird is found to have a name in the local indigenous language, the weight of evidence shifts to its being merely a new observation rather than a new phenomenon. If the bird has no name in the local language, confidence that it has indeed expanded its range is enhanced. As with the detection of trends, independent observations are a tremendous asset in interpreting significance and assigning confidence.

Table 4. Suggested development of collaboration between TEK and conventional scientific research on terrestrial ecosystems.

Potential contribution of TEK in partnership	Potential contribution of conventional science in partnership
Identify locality-specific mechanisms of change	Determine mechanisms for observed changes
Describe locality-specific impacts from environmental and ecosystem changes	Interpret observed changes and assess importance in wider contexts of space and time
Validate information from remote sensing, model output, and localized experiments	Quantify observed changes and their trends over time
Make and report winter and other observations not easily or commonly made by scientists	Identify changes not easily recorded by TEK (e.g. biogeochemical cycling such as gas fluxes)
Prioritize targets and localities for future research	Provide predictions of change

Examining Mechanisms of Change

Once a change has been observed, its cause must be examined and explained. Rarely can a study focused on one phenomenon in a natural environment adequately explain the mechanisms that caused it. Instead, mechanisms of change emerge from studying related phenomena, species, and areas and identifying similar and divergent causes of observed changes. In scientific research, experimental manipulation of environmental factors is a powerful approach to identifying mechanisms of change. Determining which environmental factors to manipulate or which types of effects to try to simulate can benefit greatly from using TEK as a starting point. Observations of change in the real world can generate hypotheses for further study. Another approach to combining TEK and science in this regard is to assess whether the results of experiments are consistent with observations of similar phenomena. In this area, TEK and scientific observations that diverge may be particularly illuminating if they can point to specific topics for closer examination. The example in Table 2 is a case in point. The explanation for divergent observations may be trivial (e.g. a change in caribou abundance), or may reveal insights into the factors that contribute to the response of lichens to warming.

CONCLUSIONS

It is clear from the comparisons above that using scientific and indigenous observations together may lead to important new partnerships of methods and observers to give better documentation and insights into current and expected environmental changes and their impacts. In this case, we have compared the results of existing studies that were conducted independently and without the expectation that they would be compared in this manner. Independence is a useful way to avoid contaminating one's results, but if comparisons are not expected then the data are often difficult to compare. It is worth noting that our retrospective and opportunistic approach—making use of whatever materials have been previously generated—gives us greater latitude in having a number of studies to draw on, but constrains us in that we have not been able to direct specific studies to examine particular questions or phenomena. Future research may benefit by combining retrospective reviews with prospective fieldwork to gather additional observations that seem likely to generate important insights when compared with existing observations from other perspectives.

The comparisons have resulted in an appreciation of both types of information, TEK and conventional science. Although the comparisons have often been difficult because of very different approaches, it is clear that both have roles to play and that partnerships could only be beneficial. Table 4 gives examples of potential roles of TEK and conventional science in partnership. Such a partnership requires extensive commitment on both sides, and investment in making data more accessible and stimulating cooperative analysis and other interactions. The role of TEK in ecological research can be greatly increased by the simple expedient of publishing more results. In addition, the involvement of TEK holders can increase the degree of collaboration in all phases of the research enterprise, while simultaneously informing local residents of the findings of scientific research that may be relevant to them and their communities.

Using scientific and traditional observations and knowledge together may produce further benefits as well. In the Arctic, many researchers are drawn by the relatively pristine environment untouched by people, and hence make an effort to stay away from settlements and camps. Among Arctic inhabitants, there is often a distrust of scientists or at least a lack of understanding of what they do and why (40). The benefits of combining TEK with conventional science to give new insights into environmental change can be complemented by the creation of collaborative partnerships, which in addition to producing more and better observations, may also lead to new understandings at the personal level (41).

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41. This collaboration was stimulated by contacts made during the drafting of the Arctic Climate Impact Assessment (ACIA) scientific report and represents an integration cutting across the terrestrial ecosystem assessment and the human dimensions assessment. Dyanna Jolly was instrumental in this work. The authors thank the agencies, too many to list individually, that have supported the work incorporated in this paper. Table 1: Examples that suggest agreement between TEK and conventional science on terrestrial ecosystem changes. Note that the first two address detection of trends, and the third is evidence of a new phenomenon.

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