CITIZEN SCIENCE:
THEORY AND PRACTICE

Tracking Science: An Alternative for Those Excluded by Citizen Science

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ABSTRACT

In response to recent discussion about terminology, we propose "tracking science" as a term that is more inclusive than citizen science. Our suggestion is set against a post-colonial political background and large-scale migrations, in which "citizen" is becoming an increasingly contentious term. As a diverse group of authors from several continents, our priority is to deliberate a term that is all-inclusive, so that it could be adopted by everyone who participates in science or contributes to scientific knowledge, regardless of socio-cultural background. For example, current citizen science terms used for Indigenous knowledge imply that such practitioners belong to a sub-group that is other, and therefore marginalized. Our definition for "tracking science" does not exclude Indigenous peoples and their knowledge contributions and may provide a space for those who currently participate in citizen science, but want to contribute, explore, and/or operate beyond

its confinements. Our suggestion is not that of an immediate or complete replacement of terminology, but that the notion of tracking science can be used to complement the practice and discussion of citizen science where it is contextually appropriate or needed. This may provide a breathing space, not only to explore alternative terms, but also to engage in robust, inclusive discussion on what it means to do science or create scientific knowledge. In our view, tracking science serves as a metaphor that applies broadly to the scientific community—from modern theoretical physics to ancient Indigenous knowledge.

INTRODUCTION

With their exploration of citizen science terminology, Eitzel and colleagues (2017) invited further comments and discussion from other groups, countries, and regions. We take up their invitation because language matters, and we are motivated by the exclusivity of the term "citizen science" as it's perceived by Indigenous people and immigrants. With this contribution by a diverse group of co-authors, including inventors, researchers, academics, and community workers from Europe, North America, and Africa, as well as trackers and conservationists who represent several Indigenous groups from southern Africa (***Table 1***), we introduce "Tracking Science," in the spirit of continued debate and discussion, as metaphor for activities that add to or generate scientific knowledge. Our definition of this term represents an inclusive complementary or alternative term to citizen science that spans most contributions to scientific knowledge regardless of origin. We focus our discussion on the issue of citizenship in the context of current post-colonial society, which grapples with marginalized groups such as Indigenous populations and immigrant or migrant groups, and we use conservation science as an example of disenfranchisement that can be changed to become more inclusive through the concept of tracking science. Owing to the time and expenses required to include members of Indigenous communities living in remote areas in this discussion, it is not feasible to include more communities in this initial paper. Yet, we hope that more Indigenous communities and independent tracking scientists from all parts of the world will join the discussion.

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Table 1 Authors' affiliations and commitments to tracking science.

TERMINOLOGY MATTERS

Generally speaking, the terms "science" and "scientist" are associated with someone who has academic credentials, thus someone trained formally in the scientific method, especially those working in academia or industry. But science as a process of studying or revealing knowledge about the world, based on facts learned through experiments and observation (the scientific method), is not limited to those with such qualifications and employment. Rather, more broadly, science is a way of thinking that has ancient roots with its origins in the Stone Age or Paleolithic, long before those of traditional institutions of higher learning (Johannes 1981, p. 5–9; Liebenberg 1990, 2013a; Rudgley 1999; Conner 2005; Fara 2009; Lombard and Gärdenfors 2017). Currently, the term citizen science is aimed at addressing this reality by taking deliberate steps towards widening the acknowledged contributor network to science. However, within it lies the exclusionary politics of citizenship, which is in the foreground for disenfranchised Indigenous populations as well as for millions of immigrants across the globe (Caramani and Grotz 2015; Mitchell et al. 2018; Goyes and Shouth 2019; Elklerman 2020; Palmquist 2020).

Concerns about the negative connotations of the term "citizen" were raised in 2007 at the Citizen Science Toolkit Conference at the Cornell Lab of Ornithology, which was the first citizen science conference. The term is still widely used today, but has since been tethered to negative political connotations that make some participants feel excluded by its use. For example, Eitzel et. al. (2017, p. 6) note that "using the word 'citizen' can be an issue, as this word may be defined as 'A legally recognized subject or national of a state' or 'An inhabitant of a city or town' (OED 2016). The first definition is problematic in some parts of the world where legal recognition is complex, and legal citizenship may not be relevant in many Citizen Science projects. The second definition appears to prioritize urban inhabitants. Citizenship can be more broadly construed, but the term remains problematic in practice; these difficulties also vary by country." Eitzel et. al. (2017, p. 13) further note that "it may also be inadvisable to refer to indigenous peoples as 'citizens' due to the legacies of colonialism."

Modern citizenship is a product of the nation-state wherein individuals had certain rights and obligations as allocated under the state's authority, and those vary from state to state (Isin and Turner 2002). For example, some states guarantee political rights to prisoners whilst others deny basic rights to refugees, and obligations may range from paying taxes to military service (e.g., Israel) (Isin and Turner 2002), or wealth and residency (e.g., Monaco) (Gamlen et al. 2019). Rights, however, typically include civil rights such as free speech and movement as well as the rule of law, political rights such as voting and seeking electoral office, and social rights in terms of welfare, unemployment insurance, and health care (Isin and Turner 2002). Yet from early on, efforts were made to avoid the universality of the concept—first by distinguishing between active and passive citizens (only the former of which had voting rights), and

later also by excluding inhabitants of foreign origin from any form of citizenship (Wallerstein 2003). Isin and Turner (2002) also remind us that some basic citizenship rights for previously excluded groups are remarkably recent in some countries. For example:

- The property qualifications for citizenship were abolished as recently as 1901 in Australia, 1918 in Britain, and 1920 in Canada, but such rights still excluded Indigenous populations in British settler societies, and these citizenship rights remain contentious (e.g., Horowitz et al. 2018; Barret et al. 2013; Dominguez and Luoma 2020; Latulippe and Klenk 2020). In Brazil, President Jair Bolsonaro, for instance, took a major step towards undermining the rights of Indigenous people, declaring that: "we're going to integrate those citizens and take care of all Brazilians" (Londoño 2019). This is the same approach that resulted in the Indigenous Kalahari San people losing their land rights in Botswana, effectively marginalizing them as a political minority when every person was declared a citizen (Malope and Batisani 2008; Cook et al. 2009).
- In most former colonies, voting rights for Indigenous peoples and/or non-Caucasians lagged behind that of Caucasian women often by decades; for example, since 1918 women have been able to vote, but "registered Indians" were granted the right only in 1960 in Canada and in 1969 in Quebec. In 1962, all Aboriginal and Torres Strait Islander people of Australia could vote, whereas most black men and women were effectively barred from voting in the United States until 1965, and in South Africa, voting for all citizens was achieved only in 1994. In New Zealand, Maori populations still vote in separate electorates to protect their minority rights.

Thus, whilst aiming to indicate that the inhabitants of a state were not merely subjects but holders of legal and political rights (e.g., the 1783 peace treaty between Great Britain and the United States of America referred to "the subjects of Great Britain and the citizens of the United States" [Wallerstein 2003]), "modern citizenship has systemically made certain groups strangers and outsiders" (Isin and Turner 2002; p. 3). For instance, for First Peoples, as well as for Diasporic Peoples, reference to citizenship in states created by intruders who colonized their ancestral lands may be highly problematic (Fleischmann et al. 2011). In terms of citizen science, conservation or environmental sciences provide globally relevant examples of exclusion in a field where non-scientists are often able to contribute scientifically useful knowledge. A clear bias was created since the founding of the first national parks in the United States (Kantor 2007; Jacoby 2014; Zifkin 2016), which were set aside exclusively for Caucasian use (Cagle 2019). This concept of creating national parks as showcases of nature conservation policy quickly spread across the globe—often maintaining the exclusivist scientific and cultural paradigms embedded in their colonial histories (Adams 2004). Brockington and Ingoe's (2006) analysis, for example, shows that Indigenous populations across all the continents were evicted from their ancestral lands to facilitate so-called conservation efforts. Thus, the question of citizenship is deeply embedded in the political structures surrounding aspects of the conservation and environmental sciences in ways that are antithetical to the more inclusive aims of citizen science.

It is not only disenfranchised First Nations who grapple with biased notions of citizenship. Today, we live in a diverse global society that transcends the notion of nation-states within which modern citizenship has been defined (Smith 2002). On the one hand are many highly skilled well-remunerated global "citizens" who work effortlessly across the boundaries of cities, countries, and continents according to opportunity—either physically or virtually—with little regard for the citizenship of individual nation states and with fluid concepts of national identity (e.g., Kennedy 2012; Schattle and Plate 2020; but see Swarts 2020 for government reactions). On the other hand, large-scale international migration because of poverty or warfare is of great concern for some countries and much attention is given to it (e.g., Boccagnia and Righard 2020). According to the Food and Agriculture Organization (FAO) of the United Nations, the number of international migrants increased from 153 million to 248 million between 1990 and 2015 (FAO 2018). Although the FAO draws attention to the role of migration as "an engine of economic growth, innovation and sustainable development," it acknowledges the widespread existence of "xenophobic political narratives about migration" (FAO 2018). Such large-scale migration and its inherent citizenship hierarchies make the term citizen increasingly uncomfortable for those who feel excluded as well as those wishing to be more inclusive (see Ellermann 2019 on discrimination in migration and citizenship).

Thus, set against the broad-scale First Nation socio-political marginalization and the emerging global geopolitical context discussed above—and even though the term citizen science has become well entrenched in the literature, making it difficult to replace—we suggest that it requires reconsideration, at least in some contexts.

PROBLEMS WITH ALTERNATIVE TERMS FOR CITIZEN SCIENCE

Ideally, potential alternatives should be constructive and globally inclusive to mitigate the negative political undertones or exclusion currently associated with notions of citizenship. The various terms for those who fall outside the predominant participatory citizen science models illustrate some of the problems with available terminologies. Shirk et al. (2012), for instance, briefly mention what they term collegial contributions, made by non-credentialed individuals who conduct research independently with varying degrees of expected recognition by institutionalized science and/or professionals. But they emphasize that, "[t]he contractual and collegial models lie at the far boundaries of the PPSR [Public Participation in Scientific Research] spectrum" (Shirk et al. 2012, p. 5). They focus on the center of their three models (contributory projects, collaborative projects, and co-created projects) while acknowledging that programmatic innovation often occurs at the boundaries (Shirk et al. 2012). The potential contribution of independent citizen scientists, or collegial contributors, is therefore marginalized, and the focus is on those models of citizen science that are managed by academics affiliated with formal institutions of learning, as well as scientists who work in research institutions, government, industry, and NGO sectors.

In addition to terms describing the citizens in citizen science, Eitzel et al. (2017, p. 14) consider including terms like "citizen researcher," defined as "an individual leading an activity or performing independent or collaborative research as the lead investigator." The terms "Indigenous," "traditional," or "local knowledge expert/holder" are defined as "an individual with place-based knowledge gained through lived experience or oral tradition" (Eitzel et al. 2017, p. 14). However, the term traditional is less favored because the knowledge is dynamic and "indigenous knowledge is viewed as different from science by both the holders of this knowledge and formally trained scientists" (Eitzel et al. 2017, p. 14). We find "local knowledge holder" also problematic because it implies a mere custodianship of knowledge, which is only one aspect of an Indigenous knowledge expert's contribution. It discounts knowledge production and does not recognize any original thinking or hypothetico-deductive (scientific) reasoning on the part of such individuals or groups.

Previously, some of us proposed the term "independent citizen scientist" within an "inclusive citizen science" (Liebenberg 2013a, 2015, 2017). In particular, Liebenberg et al. (2017) involved Indigenous Kalahari San trackers as co-authors (some are also co-authors on this paper). Independent citizen science would include those who work independently from academic scientists to produce scientific knowledge—including individuals and Indigenous communities. What they have in common is that both the individual and groups are seen as producing knowledge through their innate ability to engage in scientific reasoning, i.e., the type of logic used in hypothesis-based, predictive thinking. Independent citizen science is therefore a more inclusive category than the terms collegial contributors, citizen researcher, or individual citizen scientist, and includes Indigenous knowledge holders/experts. But none of these terms address the negative connotations of citizen noted by Eitzel et al. (2017), and expanded upon in our discussion above.

The exact meaning of terms such as collegial contributor, citizen researcher, individual citizen scientist and independent citizen scientist become diffused within the gamut of nomenclature, and do not roll off the tongue—that is, they are not intuitive, particularly insightful, nor inspirational, and therefore unlikely to gain traction. People beyond active engagement in the field therefore often have limited grasp on who is who in any particular context. These terms also fail to draw attention to the fact that they involve something fundamentally different from the participatory approaches to citizen science. Eitzel et al. (2017) point out that, to avoid using citizen, terms used for research projects involving Indigenous communities, such as community-based participatory research, "inherently separate projects from being considered traditional scientific research." These terms therefore marginalize Indigenous communities as belonging to a sub-group that is other than citizen scientists and scientists. (The term participatory can also give the impression of projects run by academic scientists with non-academics as assistants.) Citizen science also separates projects that involve citizens from science practiced by professional, credentialed scientists. A practical consequence is that communities who feel excluded by this term may not be able to secure funding if funders only support projects defined as citizen science.

Rather than listing alternative terms as sub-groups on the margins of citizen science, or something different from science, we propose that the solution is to find a term that is inclusive of everyone who participates in the generation of scientific knowledge.

TRACKING AS METAPHOR

As humans, we have evolved to use metaphors (perceptually, conceptually, and socially) to understand, illustrate, or emphasize the complexities and/or realities of the world we live in (Seitz 2005; Landau et al. 2010; Smith and Höfler 2015; Di Paola et al. 2020). The use of metaphors

is linked to higher levels of emotional understanding (Gelo and Mergenthaler 2012; Fetterman et al. 2016, 2020), and is well embedded in science understanding (English 1998; Cat 2001; Cameron 2013; Deignan and Semino 2020). Gerald Holton (1986, p. 234) emphasizes the importance of "the creative function of metaphor in the nascent phase of the scientific imagination." Thus, finding a strong metaphor that is simple, bold, and can be widely related to is perhaps what we need to recognize what is currently collated under citizen science as more active and inclusive—a metaphorical term without any negative socio-political connotations. Ideally, such an alternative term should be something that the most marginalized individuals and communities, such as Indigenous communities and their knowledge experts, would be comfortable with. It should also be a metaphor that applies widely, and inclusively, throughout the scientific community, including to professional, credentialed scientists.

We propose the term "tracking science" and the description of a participant as a "tracking scientist." (The term was created by co-author Michael Shermer for the title of an article on the origins of scientific thinking by co-author Liebenberg [2013b], and was proposed and used independently by co-authors Pierre du Plessis as well as Derek Keeping [2018].) The word tracking is widely used as a metaphor in the English language in ways that are commonly understood by everyone. Its use extends far beyond its original context of hunter-gatherer animal tracking. It is our hypothesis that most children in the world can recognize footprints. For example, co-author Derek Keeping observed his daughter, at the age of 19.5 months, stop at a footprint, think about it for a while, then point and say "shoes." Four-year-old Lily Wilder discovered a dinosaur footprint on Barry beach in Wales (Wood, 2021). We all recognize a track when we see one. It is one of the things we all have in common and can identify with—thus it is universally inclusive of all humans. Interestingly, no other animals track by following visual signs in the same way we humans do; we are the only species that evolved the necessary cognitive capacity for causal understanding involved in tracking (Lombard and Gärdenfors 2017; Lombard and Gärdenfors 2021; Shaw-Williams 2017). Carruthers (2002, p. 73) placed tracking at the "roots of scientific reasoning," and Tomaselli and Grant (2020, p. 2) argue that "tracking is akin to reading and played an imperative role in the intellectual development of humans and in the formation of modern-day science."

The phrase "to keep track of" can be found in *The Practical Standard Dictionary* published in 1922, and the *Collins Thesaurus* (2006) defines the phrase "keep track of something" as a synonym of the verb "monitor." Young readers not familiar with old-fashioned dictionaries can simply Google the phrase "keeping track of." That "monitor" is the first meaning suggested indicates the Google algorithm determined it is the meaning most widely used. In citizen science, the objective of most projects that involve gathering data over time is to monitor something, such as insects, birds, mammals, plants, water quality, air quality, weather, etc. Any research project that includes monitoring can be said to "keep track of something." The fact that "keep track of" is defined in dictionaries and thesauruses as an official phrase for "monitor" illustrates how widespread this meaning was, long before the notion of citizen science, and still is.

Tracking is also widely used as a metaphor in conservation biology to record biodiversity (Noss 1990; Kremen et al. 1994; Lawler et al. 2015). Examples include using geolocators to track bird or fish movements (Brlík et al. 2019; Crook et al. 2019). For almost 30 years, volunteers have been tracking monarch butterflies (Cohn 2008; Ries and Oberhauser 2015). Tracking as a metaphor can also be applied broadly to much of modern academic science; for example, amateur astronomers are tracking comets and other celestial objects (Ishiguro et al. 2014; Opitom et al. 2019). The "eye tracking" method is contributing to a wide array of scientific exploration from neuro- to medical science (e.g., Duchowski 2007; Liu et al. 2018), and single-quantum dot tracking is a powerful way to understand the dynamics of cellular organization (e.g., Dahan et al. 2003). In paleoecology, experts track the number of species over millions of years (e.g. Bobe et al. 2018). The current pandemic is being tracked by The COVID Tracking Project (*https://covidtracking.com/*), the Financial Times "Coronavirus tracker" (*ft.com*), and Bloomberg's "Tracking Covid-19" (*bloomberg.com*). We can cite many more examples but suggest that these are powerful enough to demonstrate that the tracking metaphor is already broadly applied in modern science, in both professional and amateur realms.

Tracking, as a method that involves hypothetico-deductive reasoning to track down animals (Liebenberg 2013a; Lombard and Gärdenfors 2017), is more than just a metaphor for monitoring. Animal tracks and signs (that are observed) are explained in terms of hypotheses about animal activities that have not been seen. To use a physics analogy, atoms cannot be seen—only *signs* of atoms are observed. This is illustrated by the papers on Brownian motion by Albert Einstein (1905, 1906) in which he explained that the erratic movement of pollen particles suspended in fluid is caused by impacts between atoms and the particles. At the time, the very existence of atoms was still a subject of scientific debate. Einstein created a hypothesis that confirmed the existence of atoms (Hawking 2002). Brownian motion is therefore a *sign* of atoms that cannot be seen. Jean Perrin (1913), who experimentally

confirmed Einstein's hypothesis in 1908 and deduced the mass of an individual molecule, explained at the time that they needed "to explain a complicated visible by a simple invisible" (as quoted in Fraser 2006, p. 87). Kalahari San trackers do not use mathematics, but they do create very sophisticated models of animal behavior to explain animal tracks and signs. In fact, Kalahari San trackers have been familiar with aspects of animal behavior only recently discovered by Western zoologists (Liebenberg 1990, p. 82). These models of animal behavior allow trackers to make predictions that can be confirmed empirically (by observing tracks and signs at a future time). The way trackers create hypothetical models to make predictions, including novel predictions, is analogous to the way a physicist creates mathematical models to explain/predict empirical observations (Liebenberg 2013a, p. 149–177). Tracking and physics are therefore analogous in the sense that both involve the explanation of observed phenomena in terms of causes that cannot be seen.

Even today, in particle physics, physicists cannot see subatomic particles. Instead, they observe particle tracks (Wichmann 1971, p. 9; Weidner and Sells 1980, p. 111; Fraser 2006, p. 95). Thomas Kuhn (1962, p. 196–197) explained that:

> "We do not *see* electrons, but rather their tracks or else bubbles of vapor in a cloud chamber. We do not *see* electric currents at all, but rather the needle of an ammeter or galvanometer… the position of the man who has learned about these instruments… [when] viewing a cloud chamber he sees (here literally) not droplets but the tracks of electrons, alpha particles, and so on. Those tracks are, if you will, criteria that he interprets as indices of the presence of the corresponding particles…"

We do not claim that all of physics currently uses tracking as a metaphor; merely that tracking has been used as a metaphor in physics. That the term "tracks" has been used in physics, along with the additional examples we provided of its use in other scientific fields, demonstrates how broadly tracking has been used as a metaphor in science. It is difficult to think of another metaphor that applies to Indigenous knowledge through to modern physics and scientific monitoring in general. This makes tracking science a powerful potential new metaphor that may apply universally to science without excluding anyone. Apart from tracking being understood as a methodological approach in institutionalized science, tracking science may also serve as a powerful metaphor for scientific processes practiced since our Paleolithic ancestors, through to modern Indigenous communities, modern urban and rural communities, and independent scientists. Tracking science can also be a metaphor for keeping track of science, which would include the history and philosophy of science. For example, Navaro-Yashin, (2009, p. 7), uses tracking as a metaphor when she states that "I find Kuhn's notion of 'paradigm shifts' instructive, then, not as a literal description of what goes on in anthropology and allied disciplines, but as an imaginative metaphor for how progress in knowledge is tracked and traced."

Furthermore, on a socio-political level in post-colonial contexts, it honors First Peoples worldwide as those whose ancestors practiced scientific reasoning before it became institutionalized. It credits the trackers of Indigenous hunter-gatherer cultures who still practice the art of tracking, which may have been the evolutionary origin of science (Carruthers 2002; Tomaselli and Grant 2020). Indigenous communities (especially hunter-gatherers) do not just acquire particular knowledge about the individual animals and plants around them, but also come to know generalizations or laws concerning them (Liebenberg 1990, 2013a, 2013b). In this sense, tracking has recently been used to illustrate the evolution of the distinct human trait of high-level causal reasoning, or causal network understanding (Lombard and Gärdenfors 2017). The oldest direct evidence suggests that such integrated abstract thinking was already practiced in Africa more than 60,000 years ago (e.g., Gärdenfors and Lombard 2018, 2021), enabling the creation of meaningful causal network hypotheses, forming the basis of modern science.

Tracking science is also gender-equal because anybody can track. For example, among Kalahari San hunter-gatherers, both women and men are trackers. Women returning from gathering plant foods would provide information on animal movements to hunters based on interpretation of tracks and signs. While there is traditionally a division of labor between men who hunt and women who gather plant foods, some women have been hunters themselves (independently from men), and some participated in active tracking and hunting with their male partners (Biesele and Barclay 2001). Men, women, and children also use "social track ways" to keep track of each other by tracking human footprints (Shaw-Williams 2014), and trail reading and marking may even have stimulated symbolic depictive and gestural proto-language in our deep past (Shaw-Williams 2017).

Tracking science can thus be summarized to have several metaphorical meanings:

1. It represents scientific monitoring or keeping track of scientifically relevant units and observations (such as particle or eye movement, cellular organization, biodiversity, and evolutionary trends), including both

quantitative and qualitative data sources as well as historical oral narratives.
2. It symbolizes the human capacity for hypothetico-deductive reasoning and experimentation that form the core of modern science.
3. It recognizes tracking, as practiced by ancient and modern Indigenous hunter-gatherers as the roots of a scientific way of thinking.
4. Tracking science can be a metaphor for keeping track of science, which would include the history and philosophy of science.

OUR DEFINITION OF TRACKING SCIENCE

We define tracking science as "a process that involves empirical observation, experimentation, and causal inference through scientific hypothetico-deductive reasoning, including the creation and testing of hypotheses and theories and making novel predictions, as well as comprising critical discussion and peer review, with the purpose of producing scientific knowledge about the world, regardless of who participates."

This definition is based on the hypothesis that scientific reasoning is rooted in innate properties of the modern human mind (Liebenberg 1990, 2013a, 2013b; Carruthers 2002, 2006; Lombard and Gärdenfors 2017; Pinker 2018). The various continuities between tracking and science are sufficient to warrant the claim that anyone having a capacity for sophisticated tracking will also have the basic cognitive wherewithal to engage in science (Carruthers 2006). Carl Sagan (1996, p. 314), referring to Kalahari San trackers, maintained "these formidable forensic tracking skills are science in action." Our definition recognizes continuity from the origins of scientific reasoning with the evolution of modern *Homo sapiens* hunter-gatherers in Africa more than 100,000 years ago through to modern physics, and supports the notion that hunter-gatherers may be just as rational and sophisticated in their understanding of nature as modern scientists (Liebenberg 1990, 2013a, 2013b). This continuity is illustrated by the example of Einstein's explanation of Brownian motion cited above. Continuity in science was also suggested directly by Einstein (1936, in 1954, p. 290), who maintained that "[t]he whole of science is nothing more than a refinement of everyday thinking."

Because tracking science is defined not in terms of its participants (as in citizen science, community science, or community-based participatory research), but as a process of knowledge production, it is fully inclusive. The process may involve credentialed and institutionalized academics and/or professional scientists active in the scientific peer-review process, yet it recognizes that scientific knowledge production need not always involve such individuals or groups. Tracking science therefore expands scientific endeavor and exploration beyond the confines of academia, professional science, and the participatory models of citizen science managed by academics. From an ethical point of view, where Indigenous people are involved in research, they should be acknowledged as co-authors of papers. The tracking science process, therefore, includes everyone who produces scientific knowledge through observation, reasoning, and hypothesizing or theorizing.

EXAMPLES OF TRACKING SCIENCE

The definition of tracking science describes, among other things, what Indigenous communities in Africa have been doing for more than 100,000 years (Liebenberg 1990, 2013a, 2013b). Tracking science does not propose a relativist version of Indigenous knowledge that fails to make distinctions between evidence-based scientific knowledge and mythology. Instead, it attends to the empirical elements of knowledge production across diverse sets of people that, in practice, may contribute to the larger body of scientific knowledge about the world. For example, we do not think that we should "abolish the distinction between science and fiction" (Woolgar 1988, p. 166), but should consider the politics and power involved in determining what scientific facts come to be accepted, much as science studies scholar Bruno Latour suggests (Latour 2003, 2005, p. 87–93). Tracking science addresses this issue by recognizing diverse epistemological traditions without reducing them to the stale knowledge-belief binary opposition. In this context, Hansson (2018, p. 518) explains that:

> "the discussion is often couched in terms of comparisons between 'indigenous belief systems' and modern science. This is a misguided and unfair comparison. In particular, the common comparison between modern science and the magical and religious thinking in indigenous societies is remarkably misconceived. Religious and spiritual thinking in traditional societies should be compared to religious and spiritual thinking in modern societies. Similarly, modern science should be compared to those elements in traditional societies that are most similar to modern science."

We do not seek to reproduce the bifurcation Hansson describes, and acknowledge that the lines between

scientific and religious thinking are often not as clear as this characterization. Nevertheless, we insist that similar elements of knowledge can be commensurable across societies. Tracking science is what Indigenous communities depended on for their survival for millennia—evidence-based scientific knowledge that had an objective correlation with the real world. Furthermore, in contemporary times, Indigenous communities have been involved in scientific research as well as biodiversity and environmental monitoring in as far afield as the Kalahari in Africa (Stander et al. 1997; Liebenberg et al. 2017; Keeping et al. 2018), the Arctic (Danielsen et al. 2014; Johnson et al. 2015), and Australia (Ansell and Koening 2011; Ens 2012), to name but a few examples. See also the video and article by Cross and Page (2020): Indigenous trackers are teaching scientists about wildlife *https://edition.cnn.com/2020/07/09/africa/louis-liebenberg-c2e-spc-int/index.html*. In today's world, Indigenous farmers who follow ancient traditions in performing advanced plant breeding and agricultural experiments maintain crop biodiversity by *in situ* conservation, which is much more efficient than storage of seeds (Altieri and Merrick 1987; Hanson 2019). Other examples include Aboriginal burning practices offering alternative fire regimes that have been incorporated into rangeland management in Australia (Verran 2002; Cook et al. 2012), the use of fire to manage natural resources by the Kalahari San (Humphrey et al. 2021), and local farmers contributing to soil science in the Philippines (Richelle et al. 2018).

Within the modern urban and rural context, tracking science could become the contemporary equivalent of Indigenous knowledge, local knowledge, or even vernacular knowledge (see Richelle et al. 2018), where urban and rural communities discover and develop their own scientific understanding of their environment—without the constraints of citizenship. This has been happening in the United Kingdom, and probably other parts of the world, for more than a century (Pocock et al. 2015). The Biological Records Centre, established in 1964 in the United Kingdom, is volunteer led and involves an estimated 70,000 people. Their datasets are long-term, have large geographic extent, and are taxonomically diverse. Significantly, many recorders undertake individual research projects on their own or with others, or make observations on novel interactions or behavior. They publish these in various journals and newsletters. We suggest that what the Biological Records Centre has been doing is closer to the definition of tracking science than the dominant, but not only, participatory models of citizen science, in which it is presumed that the research endeavors in which community members participate should be planned and led by professional scientists.

Perhaps one of the most inspirational scientific papers was published by The Royal Society in the journal *Biology Letters*. This paper, "Blackawton Bees," describing an original discovery on the vision of bumblebees, was designed, conducted, and written by a group of 8-10-year-old children outside of London, UK. The children asked the questions, hypothesized the answers, designed the games (the experiments) to test these hypotheses, and analyzed the data. They also drew the figures (in color pencil) and wrote the paper. The paper was inspired not by the scientific literature, but by their own observations of the world. In a sense it reveals science in its truest (most pure) form (Blackawton et al., 2010).

Our definition of tracking science would also incorporate the work of eminent independent scientists who changed how we think about the world in which we live, and produced groundbreaking scientific innovations working outside the domain of institutionalized science. These would include the 19th-century naturalists Charles Darwin and Alfred Russel Wallace, co-discoverers of natural selection, along with 20th-century giants such as Rachel Carson, Jane Goodall, and Albert Einstein. Tracking science therefore provides both opportunities and role models for young people who want to go beyond the confines of participatory citizen science. It has the potential to generate a recognized knowledge network wherein their aspirations and explorations may result in unexpected innovations in science and technology.

CONCLUSION

Citizen science resulted in the development of a new approach to doing science by involving large numbers of citizens as participants to collect huge amounts of data that could not have been accomplished by academics themselves—but, it is our contention that such data-collection efforts are intrinsically different from scientific thinking. Using the term citizen science in this way separates it from academic science, as something that may be perceived to be less than science. Furthermore, citizen science terms used for Indigenous knowledge imply that such practitioners belong to a sub-group that is other and therefore marginalized.

Our suggestion is not that tracking science should immediately replace citizen science, but can instead initially be considered a complement to it. Our priority is to establish a term that does not exclude marginalized groups such as Indigenous communities. At the same time, the ideal term should be all-inclusive, so that it could be adopted by everyone who participates in generating scientifically relevant knowledge. Our definition of tracking science breaks down barriers between credentialed academics, participatory citizen scientists, Indigenous communities,

and independent individuals without academic credentials. Instead of emphasizing a particular demographic or identity category—such as citizen or indigenous—tracking science emphasizes the process involved in generating scientific knowledge.

We therefore suggest that tracking science may provide a metaphorical breathing space for individuals and communities who do not fit into the citizen science mold or who are uncomfortable with the term citizen. It may also provide a space for people who currently participate in citizen science but who want to contribute, explore, and/or operate beyond its confinements. Even if the adoption of the tracking science metaphor may initially remain at the margins of academic science and citizen science, a relatively small number of independent tracking scientists may well make noteworthy and novel contributions to science and technology.

Tracking science can function to stimulate further debate on how the process of science, scientific thinking, and knowledge creation—regardless of who participates in it—can empower people with or without academic credentials to make novel contributions to how we understand the world. Our suggestion therefore concerns much more than developing a new, non-exclusive terminology. Finding a term that is inclusive for everyone who participates in science may also help us develop a better understanding of what it means to do science.

Finally, if current post-colonial politics and large-scale migration continues to cause the term citizen to be contentious, a viable alternative to citizen science will need to be considered sooner rather than later. We therefore call upon readers to join us in this discussion, not only to consider alternative terms that may serve as an inclusive metaphor, but to help us develop an inclusive understanding of what it means to do science.

ETHICS AND CONSENT

In anthropology Indigenous trackers are sometimes regarded as "human subjects." In this paper the Indigenous trackers are recognized as co-authors, not "subjects," and they consented to being co-authors.

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COMPETING INTERESTS

Robert Stevenson is an Associate Editor of Citizen Science: Theory and Practice, but in addition to the double-blind review he did not know who the Associate Editor was for this paper. The other authors have no competing interests to declare.

AUTHOR CONTRIBUTIONS

Louis Liebenberg and Derek Keeping engaged in oral discussions in the field with co-authors /Am //Ao, /Uase Xhukwe, Di //Xao, ≠Oma Kxao, Horekhwe (Karoha) Langwane, N≠aisa /Ui, /Ui G/aq'o, Njoxlau Kashe, Karel Benadie, James Minye, /Ui /Kxunta, ≠Oma Daqm and Dam Debe. These discussions focused on the broad issues of exclusion and the importance of being recognized in scientific research that involves them. Most of the Indigenous tracker co-authors are oralate (non-literate) and therefore did not contribute to some of the technical details of this manuscript. However, they have made substantial contributions to some of the works cited in this paper, which serves as examples of why they should be represented as co-authors of this paper. Louis Liebenberg, Marlize Lombard, Sven Ove Hansson, Mark Elbroch and Pierre du Plessis worked on the first and revised drafts of the manuscript. Michael Shermer, Megan Biesele, Peter Carruthers, Derek Keeping, Glynis Humphrey, Greg Newman, Justin Steventon, Robert Stevenson, Bettina Ludwig, Marike Louw and Michael Voysey provided further inputs and refinements to the manuscript.

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