



Smartphone Icon User Interface design for non-literate trackers and its implications for an inclusive citizen science



Louis Liebenberg^{a,*}, Justin Steventon^b, !Nate Brahman^{c,1}, Karel Benadie^c, James Minye^c, Horekhwe (Karo) Langwane^c, Quashe (/Uase) Xhukwe^c

^a Associate of Human Evolutionary Biology at Harvard University and Executive Director, CyberTracker Conservation, Noordhoek, P.O. Box 1211, 7985 Cape Town, South Africa

^b Lead Software Developer for CyberTracker Conservation and Principal Software Engineer at Microsoft, 1010 State St, Kirkland, WA 98033, USA

^c CyberTracker Conservation, Noordhoek, 7985 Cape Town, P.O. Box 1211, South Africa

ARTICLE INFO

Article history:

Received 16 October 2015

Received in revised form 20 April 2016

Accepted 28 April 2016

Available online 25 May 2016

Keywords:

Smartphone Icon User Interface

Citizen science

Tracking

CyberTracker

ABSTRACT

In 1996 we developed an Icon User Interface design for handheld computers that enabled non-literate trackers to enter complex data. When employed in large numbers over extended periods of time, trackers can gather large quantities of complex, rich biodiversity data that cannot be gathered in any other way. One significant result in the Congo was that data collected by trackers made it possible to alert health authorities to outbreaks of Ebola in wild animal populations, weeks before they posed a risk to humans. Trackers can also play a critical role in preventing the decimation of large mammal fauna due to poaching. Collectively, the seven case studies reviewed in this paper demonstrate the richness and complexity of scientific data contributed by community-based citizen science. Furthermore, trackers can also make novel contributions to science, demonstrated by scientific papers co-authored by trackers. This may have far-reaching implications for the development of an inclusive citizen science. Community-based tracking can significantly contribute to large-scale, long-term monitoring of biodiversity on a worldwide basis. However, community-based citizen science in developing countries will require international support to be sustainable.

© 2016 Elsevier Ltd. All rights reserved.

1. Introduction

With the advent of the Anthropocene the world is experiencing a period of rapid environmental change linked to human development (Corlett, 2015), such as habitat change, pollution, and climate change, which may affect ecosystem services gained from wildlife (Roy et al., 2015). Current rates of extinction are about 1000 times the background rate of extinction (Pimm et al., 2014). Monitoring biodiversity hotspots with high levels of diversity, as well as larger coldspots that are home to rare species (Kareiva and Marvier, 2003; Mouillot et al., 2013; Marchese, 2015) is therefore of increasing importance for informing conservation management (Sutherland et al., 2015).

There are too few professional ecologists to deal with the scale of environmental challenges. The development of citizen science has dramatically increased the extent and efficiency of data collection for studies in ecology and conservation (Dickinson et al., 2012; Pocock et al., 2015). Despite considerable differences in countries and cultures Danielsen

et al. (2014a) found that community members and scientists produced similar results for the status of and trends in species and natural resources. Promoting community-based citizen science could therefore significantly enrich monitoring within global environmental conventions and enhanced decision making at all levels of resource management (Danielsen et al., 2014b).

However, global biodiversity conservation is seriously challenged by gaps in the geographical coverage of existing information. Wealth, language, geographical location and security each play an important role in explaining spatial variations in data availability. (Amano and Sutherland, 2013). Yet locally based monitoring is particularly relevant in developing countries, where it can lead to rapid decisions to solve the key threats affecting natural resources, and empower local communities to better manage their resources to improve local livelihoods (Danielsen et al., 2008; Danielsen et al., 2014c).

Large mammal fauna in Africa and Asia is being decimated by illegal hunting and loss of habitat. In the future trackers can play a critical role in preventing poaching of endangered species such as rhino, elephant and tigers.

The case studies discussed in this paper will demonstrate the value of employing trackers using smartphones in large-scale, long-term monitoring of ecosystems for conservation management, especially in

* Corresponding author.

E-mail addresses: louis@cybertracker.org (L. Liebenberg), justin@steventon.com (J. Steventon).

¹ Deceased.

areas in the developing world where there are gaps in the geographical coverage. In particular, trackers can be of great value for monitoring rare and endangered species.

2. The art of tracking and scientific reasoning

The art of tracking involves the creation of a working hypothesis on the basis of initial interpretation of signs, knowledge of the animal's behavior and knowledge of the terrain (Liebenberg, 1990). Since tracks may be partly obliterated or difficult to see, they may only exhibit partial evidence, so the reconstruction of the animal's activities must be based on creative hypotheses. To interpret the footprints, trackers must use their imagination to visualize what the animal was doing to create such markings. With a hypothetical reconstruction of the animal's activities in mind, trackers anticipate and predict the animal's movements and look for signs where they expect to find them. When their expectations are confirmed, their hypothetical reconstructions are reinforced. When their expectations prove to be incorrect, they must revise their working hypotheses and investigate other alternatives.

Tracking involves a continuous process of conjecture and refutation, a characteristic feature of a theoretical science (Popper, 1963), and uses hypothetico-deductive reasoning (Liebenberg, 1990). Some of the predictions made by trackers may result in novel discoveries about animal behavior (Liebenberg, 2013). A significant feature of science is that testable hypotheses enable scientists to predict novel facts that would not otherwise have been known (Lakatos et al., 1978a).

The various continuities between tracking and science seem to be 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). Scientific reasoning may therefore be an innate ability of the human mind (Liebenberg, 2013). This may have far-reaching implications for the development of an inclusive citizen science.

2.1. An inclusive citizen science

Non-literate trackers, or “oralate trackers” (Sienaert, 2006), have made original contributions to science and have co-authored scientific papers (Berger et al., 1993; Berger et al., 1994; Liebenberg et al., 1998; Liebenberg et al., 1999; Stander et al., 1997a; Stander et al., 1997b; Elbroch et al., 2011; Pastoors et al., 2015; Pastoors et al., 2016).

Inclusion, however, should not only be understood from the point of view of professional scientists. It should also be seen from the point of view of communities who may include professional scientists into their traditional knowledge systems. For example, over the last 20 years we have been developing the CyberTracker tracker certification system to recognize traditional tracking skills (Liebenberg et al., 2010; Liebenberg et al., 2013). While the tracker certificates have been mostly awarded to African trackers, we have an increasing number of trackers in the USA and Europe receiving tracker certificates, including professional scientists. From an oralate African tracker perspective, “inclusion” means including professional scientists, among others, into traditional tracking.

In particular, Dr. Mark Elbroch, who received his PhD at the University of California, Davis, is the first tracker outside Africa to receive the Master Tracker certificate, the highest level recognized by CyberTracker. He came to Southern Africa to track with traditional African trackers and now uses his tracking skills to do research on mountain lions in the USA (in addition to using satellite telemetry collars and video camera traps).

Co-author Liebenberg finds himself mid-way between these opposite ends of the inclusive citizen science spectrum and has strived to act as a bridge between these two world views, or paradigms as Thomas Kuhn (1962) would have described them. Born in Africa, he is a self-taught tracker with no formal academic qualifications. As an independent citizen scientist he has published scientific papers in high impact peer-reviewed journals (for example Liebenberg, 2006, 2008, of which

the first paper has been cited more than 120 times), and has been appointed as an Associate of Human Evolutionary Biology at Harvard University.

Two centuries ago, almost all scientists made their living in some other profession. The rise of science as a paid profession is a relatively recent phenomenon, dating from the later part of the 19th century. Today, most citizen scientists work with professional counterparts on projects that have been designed to give amateurs a role (Silvertown, 2009). In the future most citizen science projects will rely on standardized field protocols to collect and visualize data necessary to monitor socioecological systems at multiple spatial and temporal scales (Newman et al., 2012).

Shirk et al. (2012) divide “public participation in scientific research” (PPSR) projects into five models based on degree of participation: *Contractual* projects, where communities ask professional researchers to conduct a specific scientific investigation and report on the results; *Contributory* projects, which are generally designed by scientists and for which members of the public primarily contribute data; *Collaborative* projects, which are generally designed by scientists and for which members of the public contribute data but also help to refine project design, analyze data, and/or disseminate findings; *Co-Created* projects, which are designed by scientists and members of the public working together and for which at least some of the public participants are actively involved in most or all aspects of the research process; and *Collegial* contributions, where non-credentialed individuals conduct research independently with varying degrees of expected recognition by institutionalized science and/or professionals.

The contractual and collegial models lie at the far boundaries of the PPSR spectrum. Shirk et al. (2012) focus on the center three models, while acknowledging that programmatic innovation often occurs at the boundaries.

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. The aspiration to involve volunteers in all aspects of the scientific process (from design to outputs) has been fulfilled in natural history in the UK for well over a century (Pocock et al., 2015).

The collegial model is exemplified by amateur astronomers, archeologists, and taxonomists, who often work on their own to make important contributions to science (Stebbins, 1980; Hopkins and Freckleton, 2002). In this model, professional and amateur researchers may collaborate only when an amateur writes and submits findings for peer review and publication. Although often overlooked or highly critiqued, committed amateurs can make critical contributions that may not otherwise transpire owing to a lack of resources, time, skills, or inclinations in the professional scientific community. As such, their work demands a reconsideration of expertise as exclusive to traditionally credentialed scientists (Taylor, 1995; Ellis and Waterton, 2005). In these cases, the degree of amateur participation in the research process is so extensive and independent that expert amateurs arguably adopt the traditional role of scientist-as-knowledge-producer (Shirk et al., 2012).

Inclusive citizen science recognizes that there is continuity from professional science on the one end of the spectrum through traditional knowledge among oralate communities on the other end of the spectrum. It strives to break down the barriers between professional scientists and amateur citizen scientists, thereby extending the range and capacity of the scientific community. Charles Darwin, after all, was an amateur citizen scientist.

Developing an inclusive citizen science will enable participants, regardless of their level of education, whether or not they can read or write, regardless of their cultural background, to make original contributions to science.

2.2. From theory to practice

Since hunter-gatherer culture is an oral tradition, traditional trackers cannot read or write. To overcome this barrier, the CyberTracker software was developed with an Icon User Interface that enabled expert oralate trackers to record complex geo-referenced data on animal behavior (online Appendix; Figs. 1 and 2).

In 1980 co-author Liebenberg discontinued his formal academic studies in Physics and Mathematics to conduct research on the art of tracking as an independent citizen scientist. In 1985 Liebenberg started working with co-author Brahman, as well as his father !Nam!kabe Molote (who was the inspiration for the Master Tracker certificate), Kayate and Boroh//xao of Lone Tree in the central Kalahari, Botswana. In 1991 Brahman asked Liebenberg to help them. Wildlife in the central Kalahari has been decimated by fences that cut off migration routes (Owens and Owens, 1984). They could no longer survive as hunter-gatherers and the art of tracking was dying out. After discussions around the fire, we decided that we should try to find ways to create employment for trackers. Only by developing tracking into a modern profession, will tracking itself survive into the future.

The CyberTracker field computer project started in 1996 as an Honors project under Professor Edwin Blake at the Department of Computer Science at the University of Cape Town, South Africa (Edge et al., 1996). In 1997 Liebenberg and Steventon founded CyberTracker to develop and distribute free software for conservation. CyberTracker was field tested by co-authors Benadie and Minye in the Karoo National Park in South Africa. In addition to monitoring a wide range of species, they also collected behavioral data by tracking individual rhinos. The first version of the CyberTracker software ran on an Apple Newton PDA which was hand-wired to an external Garmin GPS. As far as we

know, this was the first time that an Icon User Interface was developed that enabled non-literate users to enter complex data.

From 1999 the CyberTracker was used by Khwe trackers in the Kalahari to conduct wildlife transects in the Caprivi, Namibia (Mayes, 2002). They used Version 2 of the CyberTracker software, which ran on a PalmPilot PDA that was hand-wired to an external Garmin GPS. At that time maintenance of hardware and software in the Kalahari was a great inhibiting factor which seriously challenged the sustainability of CyberTracker counts (Mayes, 2002).

In 2001, a pilot research project was initiated at Lone Tree in the central Kalahari in Botswana. A Handspring Visor PDA with an attachable Magellan GPS Companion was used. A desktop computer, a solar panel and charger was set up in the village of Kagcae. This gave co-author Langwane, together with Brahman and Xhukwe, the opportunity to demonstrate that he can master the CyberTracker technology – not just collect data, but download the data, view the data on maps (Fig. 3), and recharge the batteries. While the project successfully demonstrated his ability to use the technology, the project lacked sufficient funding to pay trackers to collect data on an ongoing basis.

In 2008 the Western Kgalagadi Conservation Corridor (WKCC) Project was initiated with !Xo and /Gwi trackers in Botswana (Liebenberg, 2011). Version 3 of the CyberTracker software was used on a Windows Mobile PDA with an internal GPS. Community members were employed to use the CyberTracker to conduct animal track counts. The WKCC Project was sponsored by Conservation International and managed by Moses Selebatso over a three-year period.

After the CyberTracker engagement with the WKCC project the trackers have been employed in wildlife research projects to conduct animal track surveys (Derek Keeping, personal communication; Keeping, 2014; Keeping and Pelletier, 2014). However, we still need to overcome significant socio-economic challenges to make community-based citizen science viable among indigenous communities in Africa.

Perhaps one of the most significant outcomes of this project was a paper on rhino feeding behavior published in the journal *Pachyderm* (Liebenberg et al., 1999). This may be the first paper co-authored by two non-literate trackers (Benadie and Minye), based on a hypothesis Benadie proposed and confirmed with data that they gathered independently. This demonstrates that non-literate trackers can make novel contributions to science, and that scientific reasoning may therefore be an innate ability of the human mind.

2.3. Social and cultural benefits

Co-authors Brahman and Langwane were the key players in the creation of CyberTracker. Ideas for developing CyberTracker came about through their involvement in researching the depth of tracking knowledge in the Kalahari. The two, especially Langwane, also played an integral role in its pilot testing. This is tremendously important to the trackers and has major implications in the way that they have incorporated this technology into their lives, to the extent that they have come to consider themselves ‘Cyber trackers.’ Brahman took pride in his involvement in the development of CyberTracker and was quick to mention it when discussing CyberTracker. The work that they did together led to the development of a technology that utilizes Brahman’s knowledge, while also recognizing that of his ancestors. Though he has had relatively little interaction with computers, he had computer software designed specifically for his knowledge that he often regarded as an extension of himself. Brahman often referred to his ‘knowledge’ as his ‘CyberTracker.’ CyberTracker owes its very existence to the world of tracking and, to a degree, has been embraced by the trackers as such. Pierre du Plessis (2010) noted that during his fieldwork with them it was immediately evident that all of the trackers took pride in calling themselves ‘Cyber trackers.’

Empowered by their role as data collectors, CyberTracker was a domesticated technology for the trackers of the WKCC project. It became their own rather than just a tool of appropriation through the extension



Fig. 1. Karoha Langwane using the CyberTracker (Photo: Rolex/Eric Vandeville).



Fig. 2. Examples of Icon User Interface designs.

of a scientific and resource management network. As a tool that utilizes the knowledge of the trackers, it allowed them to continue learning at a time when there would otherwise be little opportunity to practice their skills to such a degree. Langwane said, “I like CyberTracker because I am learning a lot. I like using the technology. I like that I can use it to track animals.” Brahman and Langwane often expressed their desire to teach and pass on their knowledge of animals and plant life. Working with, and teaching some of the younger trackers were in fact one of the aspects of the WKCC project that they valued the most (du Plessis, 2010).

In addition, the trackers found security with the fact that CyberTracker stored the information they observed. Brahman said that: “One thing that I like is that it helps me capture the information. I like that what I see is being stored in the CyberTracker. I know that what I am doing will not disappear.” It was evident that the trackers themselves considered the data-archiving component extremely important (du Plessis, 2010).

Both the trackers and the scientist, Moses Selebatso, were able to mention ways that they are learning, and therefore benefiting, from one another. A mutual appreciation and respect of knowledge has developed through their co-production of knowledge. The trackers were influencing the scientist’s understanding on how to engage with the world and approach conservation. The trackers know things about the wildlife and have the practical skills to identify those things that

the scientists cannot. They offered a much more in-depth data collection process (du Plessis, 2010).

Perhaps the most significant benefit is the prestige that using the CyberTracker computer gives to trackers who previously were held in low esteem. Benadie and Minye found that using the CyberTracker has given them an incentive to refine their skills and has made their work in the field more meaningful. For the first time they were recognized for the work they have done. Non-literate trackers who have in the past been employed as unskilled laborers can gain recognition for their specialized expertise. The employment of trackers provides economic benefits to local communities and will help to retain traditional skills, which may otherwise be lost in the near future.

2.4. South African national parks

While the Kalahari tracker project demonstrated what is in principle possible, practical limitations include the lack of sustainable funding. In contrast, trackers employed as full-time rangers in national parks provide an opportunity to gather large quantities of data on a sustainable basis.

The potential use of the CyberTracker system for collecting ecological data in Kruger National Park (KNP), South Africa, was recognized in 2000 and the system was rapidly incorporated into KNP procedures

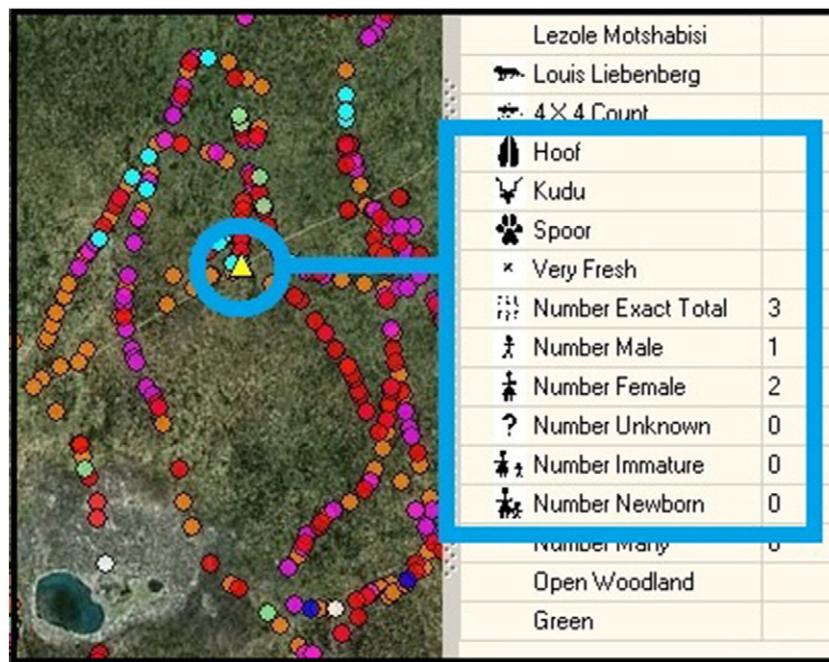


Fig. 3. Detail of the map view, showing icons representing the selected data point that show up as a yellow triangle. This enables non-literate trackers to interpret their own data on a map.

for testing and further development. Up to 120 CyberTracker units were deployed on daily patrols across the KNP (Foxcroft et al., 2009).

CyberTracker is operational in all South African national parks (Kruger and MacFadyen, 2011). Established databases include ranger patrols, vegetation condition assessments, animal behavior monitoring, rare and endangered species listings, and invasive species distribution mapping. Each database has been customized to facilitate conservation management, research and monitoring. According to MacFadyen (2009), the information gathered during these ranger patrols is used by SANParks management to: plan section patrols for area-integrity mapping; provide an early warning system for disease outbreaks; identify trends in illegal exit and entry points; and enable the detection and control of invasive alien species (Dietemann et al., 2006; Foxcroft et al., 2009; Foxcroft et al., 2010; Hui et al., 2011); and veterinary-wildlife interfaces (Ferguson and Hanks, 2010; Jori et al., 2009). In general, the ranger patrol system aims to enhance park-specific environmental management and research through field monitoring (MacFadyen, 2007).

Rhino poaching has reached a crisis level in the KNP. To bring poaching under control about 500 rangers are receiving intensive, ongoing tracker training. In addition, the CyberTracker software is being upgraded to provide real-time monitoring for anti-poaching operations.

Scientists use data collected by rangers to facilitate research and assist in making informed management decisions regarding rare species monitoring (Endangered Wildlife Trust, 2011; Murn, 2009), fire mapping, archeological inventorying, species distribution mapping, and ecosystem interactions (Burkpile et al., 2008; Somers and Hayward, 2009). Scientists also use CyberTracker to conduct their own specialized surveys and research projects.

The KNP CyberTracker database presents a unique spatial dataset, covering an extensive area. The full richness of the dataset will only emerge over time as the data are explored from a number of perspectives (Foxcroft et al., 2009). This illustrates the potential richness and complexity of data that trackers can gather.

2.5. National Indigenous Ranger CyberTracker Project in Australia

Providing sustainable funding to communities may help to bridge the gap between indigenous communities such as the Kalahari trackers

(not employed in national parks) and rangers employed on a full-time basis. This is demonstrated by the success of the National Indigenous Ranger CyberTracker Project, funded by the Australian Wildlife Services, one of the largest programs involving indigenous communities in environmental monitoring and land management programs.

The use of CyberTracker permits the rangers, landowners and their partner agencies to progressively assess activities against land and sea management goals, entering new problems as they are identified, tracking the progress of works to ensure follow-up and allowing for adjustments to be made to the work program (Ansell and Koenig, 2011).

Aboriginal lands are some of the most biodiverse and structurally intact landscapes in the country (Altman et al., 2007), but face significant environmental challenges (Woinarski et al., 2007; Altman and Whitehead, 2003). For example, fire management regimes have changed leaving large tracts of country susceptible to destructive fires (Russell-Smith et al., 2003), exotic plants and animals are widespread (Preece et al., 2010; Koenig et al., 2003) and many native species are in decline (Woinarski et al., 2010).

Indigenous ranger groups have forged partnerships with research and training institutions, government bodies, corporations and philanthropic organizations. In recognition of the environmental services that Indigenous ranger groups provide, the Australian Government has (since 2007) been investing substantial funds to formally employ Indigenous rangers and fund their operations. This has provided a measure of stability to ranger programs by providing targeted and streamlined funding sources (May, 2010).

CyberTracker software has been shown to be highly useful to the Rangers as demonstrated by its high uptake. Factors that have contributed to its successful uptake include inherent properties of the software, the 'bottom-up' approach of Ranger staff to the development of CyberTracker methodologies and the support received from external organizations. As CyberTracker is fully customizable, data applications were developed to suit the exact purposes of the Ranger programs. A key to this has been that the rangers themselves had an important role in designing the questions and the way in which they are asked in the data applications. CyberTracker enables the Rangers to get instant feedback for the work they undertake on a daily basis. This feedback also fosters a sense of pride and satisfaction for all members of the team (Ansell and Koenig, 2011).

The Federal Government, recognizing its potential to inform their decision making, has created CyberTracker support positions through their IPA program. It is anticipated that the organized collection of such quantitative operational data across Australia will demonstrate the very large contribution by Indigenous Australians to the management of Australia's land and sea environments (Ansell and Koenig, 2011).

2.6. Detecting Ebola outbreaks in Central Africa

A significant potential value of long term biodiversity monitoring by communities is that outbreaks of infectious diseases may be detected in time to avert the tragic loss of human lives. The employment of trackers in developing countries may therefore also help to prevent the spread of infectious diseases to the international community.

The recent outbreak of Ebola in West Africa has resulted in huge cost in human lives and economic losses. Even the indirect economic impact in Africa as a whole has been huge, as tourists have canceled visits to Africa due to the fear of Ebola. In future it may be more cost-effective to monitor signs of potential outbreaks of Ebola among wildlife, especially along trade routes that may spread Ebola to highly populated areas.

From 2001 to 2007 the CyberTracker Monitoring Program in central Africa was funded by the European Commission (*CyberTracker Monitoring Programme, 2007*). At the time of the Ebola outbreak in 2001 the only data available was CyberTracker patrol data that showed the presence of lowland gorilla before the outbreak of Ebola, and the absence of gorilla over a large area after the outbreak. During the Ebola outbreaks in Gabon and the Republic of Congo from 2001 to 2003 CyberTracker data showed a significant drop in animal numbers by monitoring signs of gorilla, chimpanzee, duiker and bush pig. Wild animal outbreaks began before each of the five human Ebola outbreaks. Twice it was possible to alert the health authorities to an imminent risk for human outbreaks, weeks before they occurred (Rouquet et al., 2005).

What is significant is that this data, based on tracks and signs, cannot be gathered in any other way, demonstrating the critical role of citizen science in biodiversity monitoring.

2.7. Socio-economic sustainability of community-based citizen science

Attributes of successful citizen science programs include fostering long-term community-level involvement, appropriate cyberinfrastructure, engaging under-represented audiences, ensuring financial stability, and effectively disseminating results (Bonney et al., 2009). However, as citizen science programs adopt new technologies, sensitivity to social, cultural, economic, and political factors will be critical to the success of projects that cross boundaries and involve local/traditional ecological knowledge (Ballard et al., 2008).

Most citizen science projects involve communities in developed countries where relative wealth allows individuals to volunteer time for environmental monitoring projects. For example, large numbers of relatively wealthy people worldwide engage in bird watching in their spare time, making eBird one of the largest citizen science projects. eBird engages the global bird-watching community to collect more than five million bird observations every month and to submit them to a central database where they can be analyzed to document the abundance and distribution of bird populations (Bonney et al., 2014).

In contrast, most indigenous trackers in developing countries live in communities with high levels of poverty. The most successful programs involving indigenous trackers are those where government funding has sustained employment in national parks, protected areas and where communal land is owned by indigenous communities.

Payments for environmental services (PES) are increasingly promoted as an economic mechanism that could potentially address socio-economic and environmental conservation objectives in developing

regions. However, the reporting and conditionality requirements of PES projects can be inhibitory, particularly for people with low environmental monitoring or administration capacity. Indigenous Land and Sea Management groups in remote northern Australia have combined Indigenous ecological knowledge, Western science and the CyberTracker technology to record and monitor the ecological outcomes of their land management activities to facilitate engagement with mainstream economies in Australia (Ens, 2012).

The Kalahari trackers involved in the CyberTracker research and development program have played a central role in demonstrating the potential value of employing expert trackers in scientific research and monitoring. However, due to the lack of sustainable funding, these projects have been short-lived with limited socio-economic benefits. While trackers in other projects have enjoyed significant benefits from the CyberTracker program, it is a rather sad irony that the Kalahari trackers, who have made the most important contribution to the development of the CyberTracker software, have enjoyed the least significant socio-economic benefits.

In many developing countries, community-based citizen science cannot be sustained by volunteer participation, private donations or even government funding. Yet the highest levels of traditional tracking expertise are often found in the poorest, most marginalized communities.

Global biodiversity conservation is seriously challenged by gaps in the geographical coverage of existing information. Wealth, language, geographical location and security each play an important role in explaining spatial variations in data availability; but these are not necessarily countries with high biodiversity (Amano and Sutherland, 2013). These barriers can to some extent be overcome by creating employment for indigenous trackers in developing countries; the use of icons and alias names to overcome language barriers; the use of CyberTracker in law enforcement in protected areas; and the proven record of CyberTracker projects in remote areas like the Kalahari, the Congo and many other projects in remote areas worldwide (www.cybertracker.org).

Unless governments and non-governmental organizations involve local stakeholders, environmental monitoring will tend to remain an isolated academic exercise that is primarily undertaken for the benefit of national and international stakeholders. Involving local communities in monitoring will both enhance management responses across spatial scales, and improve the speed of decision-making to tackle negative environmental trends (Danielsen et al., 2010).

Within the context of anthropogenic climate change, biodiversity monitoring should be recognized as a global, international concern. Just as climate change requires an international solution, community-based citizen science in developing countries will require international support to be sustainable.

3. Conclusion

Developing the CyberTracker Icon User Interface design for non-literate trackers demonstrated that indigenous trackers can gather complex and rich data. When employed in large numbers over extended periods of time, trackers can gather large quantities of biodiversity data that cannot be gathered in any other way, especially in areas where there are gaps in the geographical coverage. In particular, trackers can be of great value in monitoring rare and endangered species, since they can track down individual animals.

One significant result in the Congo was that data collected by trackers made it possible to alert health authorities to outbreaks of Ebola in wild animal populations, weeks before they posed a risk to humans. The employment of trackers in developing countries may therefore help to prevent the spread of infectious diseases to the international community.

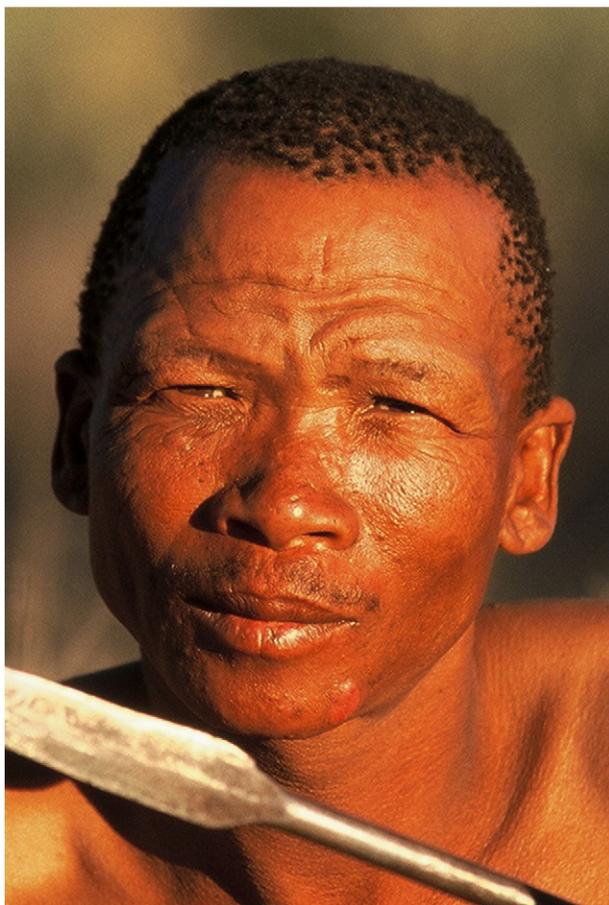
Large mammal fauna in Africa and Asia is being decimated by illegal hunting and loss of habitat. In the future trackers can play a critical role

in preventing poaching of endangered species such as rhino, elephant and tigers.

Scientific reasoning may well be an innate ability of the human mind. The implication of this theory is that an inclusive citizen science will enable participants, regardless of their level of education, whether or not they can read or write, regardless of their cultural background, to make original contributions to science.

Within the context of anthropogenic climate change, biodiversity monitoring is a global, international concern. Community-based citizen science in developing countries will require international support to be sustainable.

Dedication



After submitting the first draft of our manuscript, co-author !Nate Brahman passed away on 20 January 2016. Over the last 30 years !Nate played a central role in the development of the ideas, projects and software reviewed in this paper. In 1990 !Nate risked his own life to save the life of Liebenberg who almost died of heatstroke while running the persistence hunt (Liebenberg, 2006). We would like to dedicate this paper to his memory.

Conflict of interest

CyberTracker Conservation NPC is a non-profit Public Benefit Organization. Louis Liebenberg is the Executive Director and Justin Steventon the Lead Software Developer. The late !Nate Brahman, and Karel Benadie, James Minye, Horekhwe (Karooha) Langwane and Quashe (/Uase) Xhukwe played a central role in the field development of the CyberTracker software.

Acknowledgments

We would like to thank the anonymous reviewers for their constructive criticism and suggestions. The development of the CyberTracker software has been made possible with grants from the European Commission External Aid Contract ref. nr.: B7-6200/02/0407/TF, the JRS Biodiversity Foundation and Esri.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <http://dx.doi.org/10.1016/j.biocon.2016.04.033>.

References

- Altman, J.C., Whitehead, P., 2003. Caring for country and sustainable indigenous development: opportunities, constraints and innovation. Centre for Aboriginal Economic Policy Research Working Paper 20. Australian National University, Canberra.
- Altman, J.C., Buchanan, G., Larsen, L., 2007. The environmental significance of the indigenous estate: natural resource management as economic development in remote Australia. Centre for Aboriginal Economic Policy Research Working Paper 286. Australian National University, Canberra.
- Amano, T., Sutherland, W.J., 2013. Four barriers to the global understanding of biodiversity conservation: wealth, language, geographical location and security. *Proc. R. Soc. Lond. B Biol. Sci.* 280 (1756), 20122649.
- Ansell, S., Koenig, J., 2011. CyberTracker: an integral management tool used by rangers in the Djelk indigenous protected area, Central Arnhem land, Australia. *Ecol. Manag. Restor.* Vol. 12 (1) April 2011.
- Ballard, H.L., Trettevick, J.A., Collins, D., 2008. Comparing participatory ecological research in two contexts: an immigrant community and a native American community on Olympic Peninsula, Washington. In: Wilmsen, C., Elmendorf, W., Fisher, L., et al. (Eds.), *Partnerships for Empowerment: Participatory Research for Community-Based Natural Resource Management*. Earthscan, London, UK, and Sterling, VA.
- Berger, J., Cunningham, C., Gawuseb, A., Lindeque, M., 1993. 'Costs' and short-term survivorship of hornless black rhinos. *Conserv. Biol.* 7, 920–924.
- Berger, J., Cunningham, C., Gawuseb, A., 1994. The uncertainty of data and dehorning black rhinos. *Conserv. Biol.* 8, 1149–1152.
- Bonney, R., Cooper, C.B., Dickinson, J., et al., 2009. Citizen science: a developing tool for expanding science knowledge and scientific literacy. *Bioscience* 59, 977–984.
- Bonney, R., Shirk, J.L., Phillips, T.B., Wiggins, A., Ballard, H.L., Miller-Rushing, A.J., Parrish, J.K., 2014. Next steps for citizen science. *Science* 343 (6178), 1436–1437.
- Burkepile, D., Smith, M.D., Fynn, R.W.S., Knapp, A.K., 2008. Interactions between herbivore size and fire regime on plant community structure. In: Parks, S.A.N. (Ed.), *Reports on Scientific Research Projects Undertaken in the Savanna Parks of the South African National Parks During 2008*. Project Reports KNP 15/1/2–2008. SANParks, Pretoria, p. 23.
- Carruthers, P., 2006. *The Architecture of the Mind*. Oxford University Press, Oxford.
- Corlett, R.T., 2015. The Anthropocene concept in ecology and conservation. *Trends Ecol. Evol.* 30, 36–41.
- CyberTracker Monitoring Programme, 2007. EC Grant Contract—External Aid Contract Ref. No.: B7-6200/02/0407/TF.
- Danielsen, F., Burgess, N.D., Balmford, A., Donald, P.F., Funder, M., Jones, J.P., ... Yonten, D., 2008. Local participation in natural resource monitoring: a characterization of approaches. *Conserv. Biol.* 23 (1), 31–42.
- Danielsen, F., Burgess, N.D., Jensen, P.M., Pirhofer-Walzl, K., 2010. Environmental monitoring: the scale and speed of implementation varies according to the degree of people's involvement. *J. Appl. Ecol.* 47 (6), 1166–1168.
- Danielsen, F., Jensen, P.M., Burgess, N.D., Altamirano, R., Alviola, P.A., Andrianandrasana, H., Young, R., 2014a. A multicountry assessment of tropical resource monitoring by local communities. *Bioscience* 64 (3).
- Danielsen, F., Pirhofer-Walzl, K., Adrian, T.P., Kapijimpanga, D.R., Burgess, N.D., Jensen, P.M., ... Madsen, J., 2014b. Linking public participation in scientific research to the indicators and needs of international environmental agreements. *Conserv. Lett.* 7 (1), 12–24.
- Danielsen, F., Topp-Jørgensen, E., Levermann, N., Løvstrøm, P., Schiøtz, M., Enghoff, M., Jakobsen, P., 2014c. Counting what counts: using local knowledge to improve Arctic resource management. *Polit. Geogr.* 37 (1), 69–91.
- Dickinson, J.L., Shirk, J., Bonter, D., Bonney, R.L., Crain, R., Martin, J., Phillips, T., Purcell, K., 2012. The current state of citizen science as a tool for ecological research and public engagement. *Front. Ecol. Environ.* 10, 291–297.
- Dietemann, V., Lubbe, A., Crewe, R.M., 2006. Human factors facilitating the spread of a parasitic honeybee in South Africa. *J. Econ. Entomol.* 99, 7–13. [http://dx.doi.org/10.1603/0022-0493\(2006\)099\[0007:HFFTSO\]2.0.CO;2](http://dx.doi.org/10.1603/0022-0493(2006)099[0007:HFFTSO]2.0.CO;2).
- du Plessis, P., 2010. Tracking knowledge: science, tracking, and technology. A Dissertation Submitted in Partial Fulfilment of the Requirements for the Award of the Degree of Master of Social Science. Faculty of the Humanities. University of Cape Town.
- Edge, J., Foster, A., Steventon, L., 1996. Field computers for animal tracking. Honours Project. Department of Computer Science, University of Cape Town.
- Eibroch, M., Mwampamba, T.H., Santos, M.J., Zylberberg, M., Liebenberg, L., Minye, J., Mosser, C., Reddy, E., 2011. The value, limitations, and challenges of employing local experts in conservation research. *Conserv. Biol.* 25 (6), 1195–1202.
- Ellis, R., Waterton, C., 2005. Caught between the cartographic and the ethnographic imagination: the whereabouts of amateurs, professionals, and nature in knowing

- biodiversity. *Environment and Planning D: Society and Space* 23, 673–693. <http://dx.doi.org/10.1068/d353t>.
- Endangered Wildlife Trust, 2011. 'The endangered wildlife trust: birds of prey programme. Registered SANParks research project', viewed 04 February 2011, from <https://www.ewt.org.za/WHATWEDO/OurProgrammes/BirdsofPreyProgramme.aspx>
- Ens, E.J., 2012. Monitoring outcomes of environmental service provision in low socio-economic indigenous Australia using innovative Cybertracker technology. *Conserv. Soc.* 10 (1), 42–52.
- Ferguson, K. Hanks, J. (eds.), 2010. 'Fencing impacts: A Review of the Environmental, Social And Economic Impacts of Game and Veterinary Fencing in Africa with Particular Reference to the Great Limpopo and Kavango-Zambezi Transfrontier Conservation Areas', Mammal Research Institute, Pretoria, viewed 04 February 2011, from http://www.wcs-ahead.org/gltfca_grants/grants.html
- Foxcroft, L.C., Richardson, D.M., Rouget, M., MacFadyen, S., 2009. Patterns of alien plant distribution at multiple spatial scales in a large national park: implications for ecology, management and monitoring. *Divers. Distrib.* 15, 367–378.
- Foxcroft, L.C., Jarošik, V., Pyšek, P., Richardson, D.M., Rouget, M., 2010. Protected area boundaries as a natural filter of plant invasions from surrounding landscapes. *Conserv. Biol.* 25 (2), 400–405. <http://dx.doi.org/10.1111/j.1523-1739.2010.01617.x>
- Hopkins, G.W., Freckleton, R.P., 2002. Declines in the numbers of amateur and professional taxonomists: implications for conservation. *Anim. Conserv.* 5 (3), 245–249. <http://dx.doi.org/10.1017/S1367943002002299>
- Hui, C., Foxcroft, L.C., Richardson, D.M. & MacFadyen, S., 2011. 'Defining optimal sampling effort for large-scale monitoring of invasive alien plants: a Bayesian method for estimating abundance and distribution', *J. Appl. Ecol.*, viewed n.d., from doi: <http://onlinelibrary.wiley.com/doi/http://dx.doi.org/10.1111/j.1365-2664.2011.01974.x/abstract>. doi:<http://dx.doi.org/10.1111/j.1365-2664.2011.01974.x>
- Jori, F., Vosloo, W., Du Plessis, B., Bengis, R., Brahmabatt, D., Gummow, B., et al., 2009. A qualitative risk assessment of factors contributing to foot and mouth disease outbreaks on the western boundary of Kruger national park. *Revue Scientifique et Technique OIE* 28 (3), 917–933.
- Kareiva, P., Marvier, M., 2003. Conservation biodiversity coldspots. *Am. Sci.* 91, 344–351.
- Keeping, D., 2014. Rapid assessment of wildlife abundance: estimating animal density with track counts using body mass–day range scaling rules. *Anim. Conserv.* <http://dx.doi.org/10.1111/acv.12113>.
- Keeping, D., Pelletier, R., 2014. Animal density and track counts: understanding the nature of observations based on animal movements. *PLoS One* 9 (5), e96598. <http://dx.doi.org/10.1371/journal.pone.0096598>.
- Koenig, J., Griffiths, A.D., Godjuwa, C., Campion, O., 2003. Aerial survey of vertebrates in the Mann river district, Central Arnhem land. *Northern Territory Naturalist* 17, 7–19.
- Kruger, J.M., MacFadyen, S., 2011. Science support within the South African National Parks adaptive management framework. *Koedoe* 53 (2), Art. #1010. <http://dx.doi.org/10.4102/koedoe.V53i2.1010> 7 pages.
- Kuhn, T.S., 1962. *The Structure of Scientific Revolutions*. The University of Chicago Press, Chicago.
- Lakatos, I., Worrall, J., Currie, G., 1978a. *The methodology of scientific research programmes*. Philosophical Papers Vol. 1. Cambridge University Press, Cambridge.
- Liebenberg, L., 1990. *The Art of Tracking*. Cape Town: David Philip Free pdf download at <http://www.cybertracker.org/science/books>
- Liebenberg, L., 2006. Persistence hunting by modern hunter-gatherers. *Curr. Anthropol.* 47, 1017–1025.
- Liebenberg, L., 2008. The relevance of persistence hunting to human evolution. *J. Hum. Evol.* 55 (2008), 1156–1159.
- Liebenberg, L., 2011. The Western Kgalagadi Conservation Corridor Project. <http://www.cybertracker.org/downloads/tracking/Liebenberg-2011-WKCC-Report.pdf>
- Liebenberg, L., 2013. *The Origin of Science*. Cape Town: CyberTracker Free pdf download at <http://www.cybertracker.org/science/books>
- Liebenberg, L.W., Blake, E., Steventon, L.W., Benadie, K., Minye, J., 1998. Integrating traditional knowledge with computer science for the conservation of biodiversity. Paper Presented at the 8th International Conference on Hunting and Gathering Societies. Japan, Osaka.
- Liebenberg, L., Steventon, L., Benadie, K., Minye, J., Jan–Dec 1999. *Rhino Tracking with the CyberTracker Field Computer*. Pachyderm 27.
- Liebenberg, L., Louw, A., Elbroch, M., 2010. *Practical Tracking*. Stackpole Books, Mechanicsburg.
- Liebenberg, L., Masia, W., Pinto, J., Louw, A., Elbroch, M., 2013. *CyberTracker Tracker Evaluations* <http://www.cybertracker.org/downloads/tracking/CyberTracker-Tracker-Evaluations-July-2013.pdf>.
- MacFadyen, S., 2007. 'CyberTracker: Conservation in the palm of our hands', viewed 04 February 2011, from http://www.sanparks.org/parks/kruger/conservation/scientific/gis/CyberTracker_Poster.pdf
- MacFadyen, S., 2009. 'South African National Parks CyberTracker Programme', viewed 04 February 2011, from <http://www.sanparks.org/parks/kruger/conservation/scientific/gis/cybertracker.php>
- Marchese, C., 2015. Biodiversity hotspots: a shortcut for a more complicated concept. *Global Ecology and Conservation*. 3, 297–309.
- May, K., 2010. *Indigenous cultural and natural resource management and the emerging role of the working on country program*. Centre for Aboriginal Economic Policy Research Working Paper 65. Australian National University, Canberra.
- Mayer, S., 2002. *CyberTracker Applications in Namibia*. <http://www.cybertracker.org/downloads/tracking/Mayer-2002-CyberTracker-Applications-in-Namibia.pdf>
- Mouillot, D., Bellwood, D.R., Baraloto, C., Chave, J., Galzin, R., Harmelin-Vivien, M., Kulbicki, M., Lavergne, S., Lavoire, S., Mouton, N., Paine, C.E., Renaud, J., Thuiller, W., 2013. Rare species support vulnerable functions in high-diversity ecosystems. *PLoS Biol.* 11, e1001569.
- Murn, C., 2009. *Ecological characteristics of the white-headed vulture Trigoniceps occipitalis in Southern Africa*. In: Parks, S.A.N. (Ed.), *Reports on scientific research projects undertaken in the savannah national parks of South African National Parks during the year 2009 and projects that were completed during 2008*. Research Project Reports 2009, KNP 15/1/2–2009. SANParks, Pretoria, p. 157.
- Newman, G., Wiggins, A., Crall, A., Graham, E., Newman, S., Crowston, K., 2012. The future of citizen science: emerging technologies and shifting paradigms. *Front. Ecol. Environ.* 10 (6), 298–304.
- Owens, M., Owens, D., 1984. *Cry of the Kalahari*. Fontana, London.
- Pastors, A., Lenssen-Erz, T., Ciqae, T., Ui, K., Thao, T., Bégouën, R., Biesele, M., Clottes, J., 2015. Tracking in caves: experience based reading of Pleistocene human footprints in French caves. *Camb. Archaeol. J.* <http://dx.doi.org/10.1017/S0959774315000050> Available on CJO.
- Pastors, A., Lenssen-Erz, T., Breuckmann, B., Ciqae, T., Ui, K., Rieke-Zapp, D., Thao, T., 2016. Experience Based Reading of Pleistocene Human Footprints in Pech-Merle Quarry International <http://dx.doi.org/10.1016/j.quaint.2016.02.056>.
- Pimm, S.L., Jenkins, C.N., Abell, R., Brooks, T.M., Gittleman, J.L., Joppa, L.N., Raven, P.H., Roberts, C.M., Sexton, J.O., 2014. The biodiversity of species and their rates of extinction, distribution, and protection. *Science* 344, 1246752 (2014).
- Pocock, M.J.O., Roy, H.E., Preston, C.D., Roy, D.B., 2015. The biological records centre: a pioneer of citizen science. *Biol. J. Linn. Soc.* 115, 475–493.
- Popper, K.R., 1963. *Conjectures and Refutations*. Routledge and Kegan Paul, London.
- Preece, N., Harvey, K., Hempel, C., Woinarski, J.C.Z., 2010. Uneven distribution of weeds along extensive transects in Australia's northern territory points to management solutions. *Ecol. Manag. Restor.* 11, 127–134.
- Rouquet, P., Froment, J.-M., Bermejo, M., Kilbourne, A., Karesch, W., Reed, P., et al., 2005 Feb. Wild 734 animal mortality monitoring and human Ebola outbreaks, Gabon and Republic of Congo, 2001–2003. *Emerg. Infect. Dis.* 11 (2), 283–290. <http://dx.doi.org/10.3201/eid1102.040533>.
- Roy, H.E., Preston, C.D., Roy, D.B., 2015. Fifty years of the biological records Centre. *Biol. J. Linn. Soc.* 115, 469–474.
- Russell-Smith, J., Yates, C.P., Edwards, A., et al., 2003. Contemporary fire regimes of northern Australia, 1997–2001: change since aboriginal occupancy, challenges for sustainable management. *Int. J. Wildland Fire* 12, 283–297.
- Shirk, J.L., Ballard, H.L., Wilderman, C.C., Phillips, T., Wiggins, A., Jordan, R., McCallie, E., Minarchek, M., Lewenstein, B.V., Krasny, M.E., Bonney, R., 2012. Public participation in scientific research: a framework for deliberate design. *Ecol. Soc.* 17 (2), 29. <http://dx.doi.org/10.5751/ES-04705-170229>.
- Sienaeft, E., February 8th, 2006. "Levelling the oral-literate playing field: Marcel Jousse's laboratory of awareness". Presentation at the Centre for Comparative Literature 6. University of Toronto Pdf available on the website of the Institut Européen de Mimopédagogie <http://mimopedagogie.pagesperso-orange.fr/Bibliographie/bibliographie.htm>
- Silvertown, J., 2009. A new dawn for citizen science. *Trends Ecol. Evol.* Vol. 24 (9), 467–471.
- Somers, M., Hayward, M., 2009. Impact of climate change on predator prey preferences. In: Parks, S.A.N. (Ed.), *Reports on scientific research projects undertaken in the savannah national parks of South African National Parks during the year 2009 and projects that were completed during 2008*. Research Project Reports 2009, KNP 15/1/2–2009. SANParks, Pretoria, p. 215.
- Stander, P.E., Ghau, /., Tsisaba, D., #Oma, /., /Ui, 1997a. Tracking and the interpretation of spoor: a scientifically sound method in ecology. *J. Zool. (Lond.)* 242, 329–341.
- Stander, P.E., Haden, P.J., Kazece, /., Ghau, /., 1997b. The ecology of asociality in Namibian leopards. *J. Zool. (Lond.)* 242, 343–364.
- Stebbins, R.A., 1980. Avocational science: the amateur routine in archaeology and astronomy. *Int. J. Comp. Sociol.* 21 (1/2), 34–48.
- Sutherland, W.J., Roy, D.B., Amano, T., 2015. An agenda for the future of biological recording for ecological monitoring and citizen science. *Biol. J. Linn. Soc.* 115 (3), 779–784.
- Taylor, B., 1995. Amateurs, professionals and the knowledge of archaeology. *Br. J. Sociol.* 46 (3), 499–508. <http://dx.doi.org/10.2307/591853>.
- Woinarski, J.C.Z., MacKey, B., Nix, H., Traill, B., 2007. *The Nature of Northern Australia: Natural Values, Ecological Processes and Future Prospects*. Australian National University e-Press, Canberra.
- Woinarski, J.C.Z., Armstrong, M., Brennan, K.E.C., et al., 2010. Monitoring indicates rapid and severe decline of native small mammals in Kakadu National Park, Northern Australia. *Wildl. Res.* 37, 116–126.