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Contributed Paper

# The role of digital data entry in participatory environmental monitoring

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**Abstract:** *Many argue that monitoring conducted exclusively by scientists is insufficient to address ongoing environmental challenges. One solution entails the use of mobile digital devices in participatory monitoring (PM) programs. But how digital data entry affects programs with varying levels of stakeholder participation, from nonscientists collecting field data to nonscientists administering every step of a monitoring program, remains unclear. We reviewed the successes, in terms of management interventions and sustainability, of 107 monitoring programs described in the literature (hereafter programs) and compared these with case studies from our PM experiences in Australia, Canada, Ethiopia, Ghana, Greenland, and Vietnam (hereafter cases). Our literature review showed that participatory programs were less likely to use digital devices, and 2 of our 3 more participatory cases were also slow to adopt digital data entry. Programs that were participatory and used digital devices were more likely to report management actions, which was consistent with cases in Ethiopia, Greenland, and Australia. Programs engaging volunteers were more frequently reported as ongoing, but those involving digital data entry were less often sustained when data collectors were volunteers. For the Vietnamese and Canadian cases, sustainability was undermined by a mismatch in stakeholder objectives. In the Ghanaian case, complex field protocols diminished monitoring sustainability. Innovative technologies attract interest, but the foundation of effective participatory adaptive monitoring depends more on collaboratively defined questions, objectives, conceptual models, and monitoring approaches. When this foundation is built through effective partnerships, digital data entry can enable the collection of more data of higher quality. Without this foundation, or when implemented ineffectively or unnecessarily, digital data entry can be an additional expense that distracts from core monitoring objectives and undermines project sustainability. The appropriate role of digital data entry in PM likely depends more on the context in which it is used and less on the technology itself.*

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**Keywords:** citizen science, community-based monitoring, participatory monitoring and management, public participation in scientific research, traditional ecological knowledge

El Papel del Registro Digital de Datos en el Monitoreo Ambiental

**Resumen:** *Mucha gente argumenta que el monitoreo realizado exclusivamente por científicos es insuficiente para enfrentar los retos ambientales contemporáneos. Una solución implica el uso de instrumentos digitales móviles en programas de monitoreo participativo (MP). Sin embargo, no es clara la manera en que el registro de datos afecta a los programas con varios niveles de participación de actores, desde no científicos recolectando datos de campo y administrando cada etapa del programa de monitoreo. Revisamos los éxitos, en términos de intervenciones de manejo y sustentabilidad, de 107 programas de monitoreo descritos en la literatura (programas de aquí en adelante) y los comparamos con casos de estudio de nuestras experiencias de MP en Australia, Canadá, Etiopía, Ghana, Groenlandia y Vietnam (casos de aquí en adelante). Nuestra revisión de literatura mostró que los programas participativos tuvieron menor probabilidad de utilizar instrumentos digitales, y 2 de nuestros casos más participativos también fueron lentos en adoptar el registro digital de datos. Los programas participativos y que utilizaron instrumentos digitales tuvieron una mayor probabilidad de reportar acciones de manejo, lo cual fue consistente con casos en Etiopía, Groenlandia y Australia. Los programas que incluyeron voluntarios fueron reportados como en marcha más frecuentemente, pero los que involucraron el registro digital de datos tuvieron menos sustento cuando voluntarios recolectaron datos. Para los casos vietnamitas y canadienses, la sustentabilidad fue minada por una disparidad entre los objetivos de los actores. En caso ghanés, la sustentabilidad del monitoreo disminuyó debido a los complejos protocolos de campo. Las tecnologías innovadoras atraen el interés, pero la base del monitoreo adaptativo participativo efectivo depende más de preguntas, objetivos, modelos conceptuales y métodos de monitoreo definidos colaborativamente. Cuando esta base se construye mediante colaboraciones efectivas, el registro digital de datos puede permitir la recolección de datos de mayor calidad. Sin esta base, o cuando implementada infectiva o innecesariamente, el registro digital de datos puede ser un costo adicional que distrae de los objetivos medulares del monitoreo y socava la sustentabilidad del proyecto. El papel adecuado del registro digital de datos en MP depende más del contexto en que es utilizado que en la tecnología misma.*

**Palabras Clave:** ciencia ciudadana, conocimiento ecológico tradicional, monitoreo basado en comunidades, monitoreo y manejo participativo, participación de público en la investigación científica

## Introduction

It is widely acknowledged that more effective environmental monitoring is needed to support management in the face of rapid global change (Lindenmayer & Likens 2009). However many have argued that, based on currently available resources, monitoring executed exclusively by professional scientists is insufficient to address these ongoing challenges (Danielsen et al. 2005; Dickinson et al. 2010). Thus, various forms of participatory monitoring (PM) are being used to increase the extent and resolution of monitoring data. The degree to which PM engages stakeholders including resource users, local residents, indigenous peoples, and interested citizens, varies from participants solely collecting data to participants leading monitoring design, implementation, and subsequent management interventions. Danielsen et al. (2009, 2014*a*) identified a spectrum of participation in monitoring, including type A, autonomous local monitoring, with no formal affiliations with professional scientists; type B, collaborative monitoring with local data interpretation, where local stakeholders undertake data collection, interpretation, or analysis, and management decision making, and external scientists can provide advice and training; type C, collaborative monitoring with external data interpretation, where local stakeholders are involved only in data collection and decision making based on monitoring results; type D, externally driven monitoring with local data collectors, where local stakeholders are involved only in data collection (commonly called citizen science); and type E, scientist-executed monitoring, where external scientists manage all aspects of the project and local stakeholders are not involved.

For much of recorded history, knowledge generation has been the domain of nonprofessionals (Miller-Rushing et al. 2012). However, over time studying the environment has become the sphere of an increasingly professional and exclusive scientific community (Miller-Rushing et al. 2012; Hård & Jamison 2013). The result was a field that privileged science and excluded other ways of understanding the environment, such as traditional ecological knowledge (TEK; Berkes 2012). However, interest is increasing in multiple knowledge systems and in participatory approaches to science, particularly in environmental monitoring (Raymond et al. 2010; Tengö et al. 2014). Concurrently the advent of mobile devices (including smartphones, personal digital assistants [PDAs], tablets, digital cameras, data loggers, and global positioning system [GPS] units) could reinforce this trend toward environmental sciences that are more participatory and inclusive (Dickinson et al. 2012; Newman et al. 2012). In particular, monitoring programs engaging TEK holders could benefit from digital data entry. Ensuring that these benefits are realized by all stakeholders will likely depend on the program's extent of participation (e.g., types A–D; Danielsen et al. 2014*a*).

Currently, monitoring that is externally driven, with participants collecting data (e.g., type D, most citizen science) is the most frequently documented form of PM (Theobald et al. 2015). This form of PM should benefit from digital data entry because it can increase the potential pool of participants; simplify data collection, transcription, and management; offer immediate feedback to data collectors; improve data diversity (e.g., photos, videos, GPS) and quality; and facilitate data dissemination (Newman et al. 2012; Teacher et al. 2013; Kim 2014). For many the outlook for digital data entry in PM is positive when used to support type D citizen science (Newman et al. 2012; Bonney et al. 2014).

Less clear is how digital data entry contributes to monitoring projects that are more participatory (e.g., types A–C; Johnson et al. 2015), particularly those seeking to engage TEK holders. Among these projects, many currently rely on limited technology (e.g., pen and paper; Stuart-Hill et al. 2005; Riseth et al. 2011; but see Ansell & Koenig 2011; Gearheard et al. 2011; Parry & Peres 2015). This could reflect a lack of access to newer digital technologies, but it may also reflect common concerns such as their high costs, training requirements, and complexity relative to paper-based protocols (Gearheard et al. 2011; Danielsen et al. 2014*b*; Kim 2014) and problems associated with monitoring programs that are highly participatory (e.g., data privacy, limited technical capacities, incompatibilities of TEK and digital data formats; Ellis 2005; Fernandez-Gimenez et al. 2007; Bonny & Berkes 2008).

Given the commitment, in terms of resources and time, necessary for programs to adopt digital tools for data collection, there is a need to explore how this technology has benefited, or detracted from, monitoring programs across the PM spectrum. We reviewed monitoring successes, in terms of management actions and project sustainability, of a sample of PM projects described in the literature (hereafter programs) to determine how success related to project characteristics such as stakeholder participation and use of digital data entry. We compared this general analysis with a detailed examination of multiple case studies based on our PM experiences with Indigenous communities in Australia, Canada, Ethiopia, Ghana, Greenland, and Vietnam (hereafter cases). These parallel analyses allowed for a comparison of broad trends and specific, contextual experiences to determine how digital devices have, and have not, contributed to the success of PM.

# Methods

## Meta-Analysis

We expanded on Danielsen et al.'s review of 107 environmental monitoring programs (2014*a*) extracted from 3,454 monitoring publications from 1989 to 2012. The terms "monitoring" and "conservation" were queried in BIOSIS Previews 2004–2012, Biological Abstracts 1990–2000, and Biological Abstracts, Reports, Reviews, and Meetings 1989–2003. Publications were selected if they described monitoring species, populations, habitats, ecosystems, or resource use. We evaluated each publication for 1 monitoring method, use of digital devices for data collection, and 2 proxies of monitoring success, did monitoring lead to management action and was monitoring ongoing at the time of publication (indicator of project sustainability).

To explain these outcomes we used 9 contextual elements, 4 of which were coded by Danielsen et al. (2014*a*) and the remainder by J.R.B., grouped into 4 categories of explanatory variables: scale and tenure (spatial extent [1–4,999 ha, 5,000–9,999 ha, etc.] and local tenure system [national park, locally managed protected area, unprotected area]); cost (funding source [entirely internal, village level; >50% internal; etc.] and amount of funding [in U.S. dollars per hectare per year] and payment of field workers [yes or no]); monitoring duration and diversity (log-transformed years monitored and number of taxonomic groups monitored [single taxon vs. multiple taxa]); public participation (level of participation [types A–E] and use of digital devices for data collection) (used when modeling management action and monitoring sustainability; Table 1). For models of each outcome variable, we omitted publications if any variables were missing values (Table 1). We ranked how these categories explained each outcome using logistic models and Akaike's corrected information criterion ($AIC_c$; Burnham & Anderson 2002). We based inferences on the top model if no competitors were within 2 $\Delta AIC_c$ and on estimates from the top two models otherwise. Uncertainty was presented as 95% confidence intervals (CI).

Many PM programs are unpublished or their characteristics go unreported. Our sample likely underrepresents smaller and younger programs and as a result the recent emergence of digital data entry. Management actions and project sustainability may not be consistently reported in the literature. Because of our small sample, we did not differentiate between the effects of different forms of digital data entry (i.e., smartphones, PDAs, tablets, digital cameras, data loggers, GPS units) and omitted contextual elements of potential importance (e.g., level of training or support provided, education or socioeconomic status of participants). Nonetheless, we believe our quantitative analysis provides an informative

**Table 1. Outcome and predictor variables, including predictor variable categories, used in logistic models based on a data from 107 environmental monitoring programs described in the literature.**

| *Variable* | *Program characteristics* |
|---|---|
| Method | |
| use of digital device | Was a digital device (e.g., GPS, still camera, video camera, smartphone, PDA, data logger, handheld computer, or radio transmitter) used for field data collection?<br>1. yes<br>2. no |
| Outcome | |
| management action | Has the monitoring project explicitly led to specific management actions?<br>1. yes<br>2. no |
| sustainability | Was monitoring ongoing at the time of publication?<br>1. yes<br>2. no |
| Predictor | |
| category 1 scale and tenure | |
| spatial extent | Total size of area monitored<br>1. ≥100,000 ha<br>2. 50,000–99,000 ha<br>3. 10,000–49,999 ha<br>4. 5,000–9,999 ha<br>5. 1–4,999 ha |
| land-tenure system | Dominant land-tenure system of area monitored<br>1. protected area under government authority<br>2. protected area managed (partially or fully) by the local communities<br>3. outside protected areas |
| category 2 cost | |
| source of funding | Who paid for monitoring?<br>1. entirely external (national or international)<br>2. >50% external<br>3. >50% internal (village or district level)<br>4. entirely internal |
| paid field workers | Were field workers paid?<br>1. yes<br>2. some<br>3. no |
| monitoring cost | How much does the monitoring program cost in US$/ha/year? |
| category 3 duration and diversity | |
| project duration | How long has the project been monitoring in years? |
| taxonomic diversity | Does the scheme monitor<br>1. >1 taxonomic group or resource<br>2. 1 taxonomic group or resource (e.g., fish) |
| category 4 public participation | |
| level of public participation | What category best describes the projects level of public participation?<br>1. scientist-executed monitoring<br>2. externally driven monitoring with local data collectors<br>3. collaborative monitoring with external data interpretation<br>4. collaborative monitoring with local data interpretation<br>5. autonomous local monitoring |
| use of digital devices | Was a digital device used for field data collection?<br>1. yes<br>2. no |

snapshot of the environmental monitoring literature with which to compare our multiple cases.

### Case Studies

We examined 6 PM cases from 6 different nations that involved monitoring projects across the PM spectrum (Fig. 1). These were selected based on our experiences through our respective research and capacity-building programs. We categorized 3 cases as type B participation: Greenland, community-based monitoring of wildlife harvests and natural resources among local communities in Disko Bugt and adjacent areas (Danielsen et al. 2014*b*); Canada, consultations regarding and trials of wildlife- and forestry-monitoring protocols conducted with digital data entry by Inuit, Gwich'in, Cree, and Anicinapek

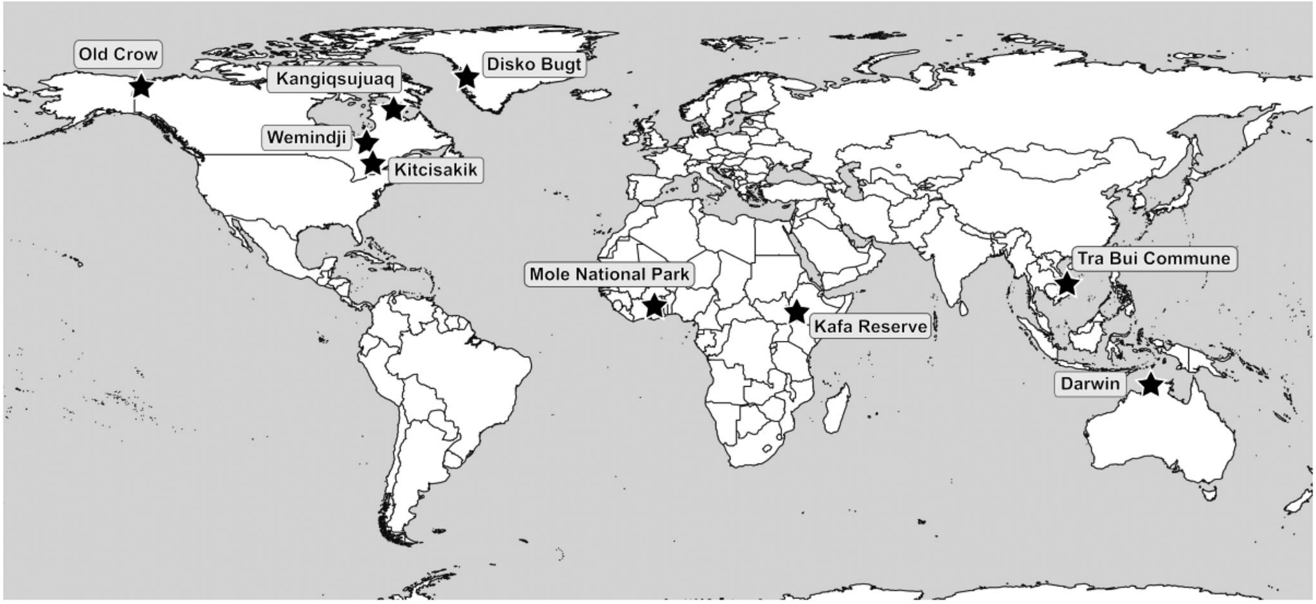


*Figure 1. Location of 6 case studies. Cases from Australia and Greenland had participants from multiple communities but are represented with just 1 star.*

communities; and Australia, natural resource monitoring and management (e.g., biodiversity, fire, cultural sites, wildlife, invasive plants and animals, marine debris, tourists) by numerous indigenous communities in northern Australia (Kennett et al. 2010). We classified 1 case as type C–Vietnam, forestry monitoring by the Ca Dong community in the Tra Bui commune (Pratihast et al. 2013), and 2 cases as type D–Ethiopia, forestry monitoring in the Kafa Biosphere Reserve of southwestern Ethiopia by local community members (Pratihast et al. 2014), and Ghana, wildlife monitoring by local indigenous community members employed by Mole National Park (Burton 2012). Detailed descriptions of each program are in Supporting Information.

These programs were established independently with no universally applied protocol. They represent a heterogeneous set of national contexts where digital data entry was used in PM. Each program used various interaction strategies to solicit participant feedback on the strengths and weaknesses of digital data entry (Brunet et al. 2014), including: participant observations, conversations, public presentations, community meetings, field trials, and interviews (Brunet et al. 2014). Because participation in the assessment was voluntary, sampling of local participants was purposive (Sue & Ritter 2012). We cannot generalize our findings beyond these cases (Yin 2014). Nevertheless, we saw value in documenting these as a heterogeneous sample of international PM projects because they highlight a variety of contexts within which these programs evolve. We believe this strategy supported both the internal and the external validity of our multiple case study (Boeije 2002; Eisenhardt & Graebner 2007). Comparing and contrasting this qualitative approach with our quantitative meta-analysis allowed us to maximize construct validity and test the repeatability of our findings (Stake 2005).

## Results

### Use of Digital Data Entry in PM

Our meta-analysis showed digital devices were more frequently used in less participatory, scientist-driven programs (i.e., types C–E, model coefficient $\beta = -0.49$ [$-0.94$, $-0.04$]; $p = 0.03$; $n = 88$ [Fig. 2]; model selection tables in Supporting Information). Similarly, the slowest adoption of digital data entry occurred in some of our most participatory cases (type B). In the Greenlandic communities, harvesters reported wildlife sightings and harvests at meetings of their Natural Resource Committees (NRC). At these quarterly meetings, individual sightings were compiled into summary reports, results were compared from the same area and season in previous years, interpreted by community members, and management actions were discussed. Participants had the option of reporting observations verbally, on paper data sheets, or with smartphones or body cameras. The majority of the 33 participants favored oral reporting. The proportion of observations documented digitally increased over time, however, in particular as the number of younger participants increased. Participants suggested digital data entry could contribute to engaging more youth in environmental monitoring and activities on the land. Two Canadian participants said: "[This digital

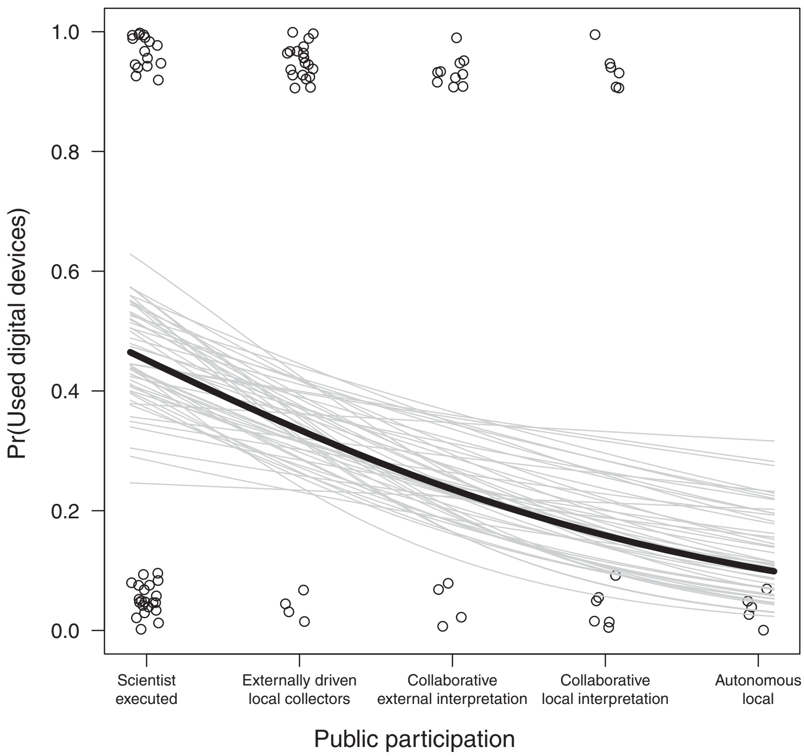


*Figure 2. The probability (pr) of a monitoring program using digital devices as a function of the degree of public participation in the program (participation levels from Danielsen et al. [2009]; thick line, mean predicted probability from the participation model; gray lines, 50 simulations of possible models based on estimated model coefficients and their standard errors [Gelman & Hill 2007]). Simulations represent the range of possible outcomes that agree with model estimates within a 95% CI. Data points (n = 88) were jittered to improve density visualization.*

device] is not useful for me because I know my territory. But for our youth, it is useful when a young hunter [is] lost" (Kitcisakik elder) and "[i]t was easy to fire up the [digital device]" for recording elder's stories (Old Crow youth).

Still, many of the Canadian participants found digital devices complicated to operate in the field and slow to record data, and they had difficulty viewing the screen, using the keyboard, reviewing data once entered, operating the device while cleaning fish, and interpreting the unilingual English interface: "[This digital device] is not so simple to use" (Kitcisakik professional) and "The GPS was not able to record a place while in a moving boat on water, no matter how slow we were moving" (Old Crow participant).

This reticence was not universal among type B cases. The Indigenous Tracker (I-Tracker) program has successfully coordinated PM frameworks with a customized CyberTracker digital data-entry platform in multiple Indigenous communities in northern Australia (previously summarized in Kennett et al. 2010; NAILSMA 2014). Run by the North Australian Indigenous Land and Sea Management Alliance Ltd (NAILSMA), the I-Tracker program engaged indigenous people, TEK holders, and professional indigenous rangers (see Commonwealth of Australia 2009) in land and sea management and monitoring activities, planning, and decision making in their communities. A most-significant-change evaluation of I-Tracker, involving 66 semistructured interviews with participants and scientists (Bessen 2013), showed that I-Tracker's digital tools facilitated the reporting of monitoring data and the transfer of TEK between elders and rangers. "Using that technology and checking with the old people, it's a good little thing. Sometimes you get a bit of debate with the old people like "nah nah that's not there, that's not right" you know and "we got it right here, that's where the place is!" [ranger] (Bessen 2013). However, it also highlighted that a key to program success was the provision of ongoing training and technical support for rangers and the highly participatory approach used to develop monitoring protocols and the digital data-entry platform. One ranger said, "... NAILSMA staff have been ... [b]ringing a lot more training and a lot more I-Trackers. What suits us and what doesn't suit us and we talk about it" [ranger] (Bessen 2013). Overall this case highlighted the importance of digital tools that are adaptable to local settings and changing community needs over time.

### Digital Data Entry, PM, and Management Actions

In our meta-analysis, programs were more likely to report management actions if they were more participatory ($\beta = 0.6$ [0.1, 1.1], $p = 0.03$, $n = 88$) and used digital devices ($\beta = 1.5$ [0.2, 2.8], $p = 0.03$; $n = 88$; Fig. 3). Management action was best explained by combining the top 2 categories of variables (public participation and duration and diversity). This maintained the positive association between management actions and participation and digital devices. In our type D case in the Kafa Biosphere Reserve of Ethiopia, the Bureau of Agriculture and Rural Development (Pratihast et al. 2014) hired 30 local community members to document forest change (alongside

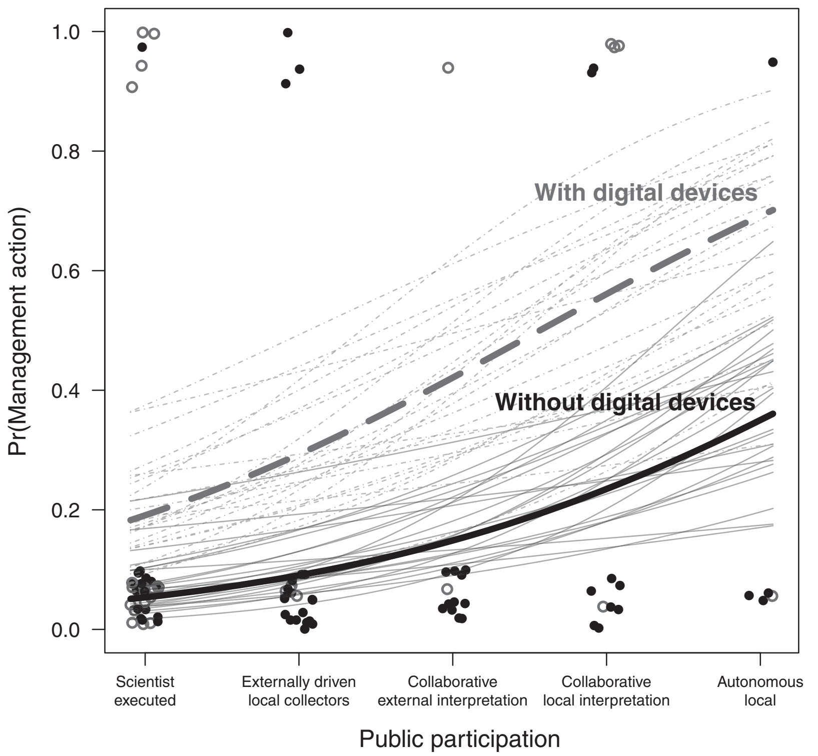


*Figure 3. The probability (*Pr*) of a publication describing specific management actions that resulted from monitoring as a function of the level of public participation (participation levels from Danielsen et al. [2009]) and the use of digital data collection (thick lines, predicted probability derived from the top model; thinner lines, 50 simulations of possible models based on estimated model coefficients and their standard errors [Gelman & Hill 2007]; solid circles and lines, programs using digital devices; open circles and dashed lines, projects operating without digital devices). Data points (*n = *88) were jittered to improve density visualization.*

other responsibilities). Participants used 2 protocols to document forest degradation, deforestation, and reforestation: paper data sheets and handheld GPS, and smartphones with integrated GPS, camera, and an Open Data Kit (ODK) interface. Participants reported that digital devices simplified data entry in the field and facilitated rapid communication of monitoring results with other community members, particularly when using social media. For example, Facebook reporting of illegal firewood extraction has drawn the attention of enforcement officials and led to the revocation of forest-use certification.

The type B cases from Greenland and Australia also showed a relationship between participation and management actions. At the NRC meetings in Greenland, management decisions (e.g., change in quota, hunting season, gear restriction, etc.) were discussed in response to monitoring results (Danielsen et al. 2014*b*). Any management actions recommended by the NRCs were presented to the local government authority. At the time of publication, this NRC-based monitoring system contributed to 14 management recommendations, including setting quotas (2 proposals), changing hunting seasons (5), identifying research needs (3), altering fishery bylaws (2), and others (2). The local municipal authority responded to 11 of these proposals. In these cases, there was no detectable effect of digital reporting on management activities, but in the Australian case the benefits of digital data entry were more apparent. I-Tracker began as a program that supported monitoring of marine and coastal management issues, then expanded to support over 30 ranger groups to monitor and manage a wide range of natural and cultural resources belonging to their communities. Digital data entry improved the capacity of rangers to record and report the results of their diverse surveillance and management activities, for example enabling them to negotiate fee-for-service contracts with Australian Customs and Northern Territory Fisheries (NAILSMA 2014) and implement locally driven scientific research (e.g., Jackson et al. 2015).

## Digital Data Entry, PM, and Monitoring Sustainability

In our meta-analysis program sustainability was best explained by combining the public participation and cost categories, which highlighted how more participatory programs, particularly those that engaged volunteer data collectors, were more frequently sustained ($\beta = 2.0$ [0.3, 3.7], $p = 0.01$; $n = 84$). Digital devices were negatively associated with project sustainability when data collectors were volunteers ($\beta = 3.6$ [$-5.6$, $-2.0$]; $n = 84$) but not when they were paid ($\beta = 0.1$ [$-0.8$, 1.0]; $n = 84$; Fig. 4). Digital data entry appeared not to enhance program sustainability. In the Vietnamese case, sustainability was entirely unrelated to the degree of participation or the data-entry protocol. Community members contributed to the design of a forest monitoring protocol with digital data entry on XLS forms and ODK. This approach had lower monitoring costs relative to professionally implemented alternatives and provided employment for community members. Nonetheless, the program was not sustained because the local Ca Dong community, an ethnic minority, were displaced from their traditional territory by the

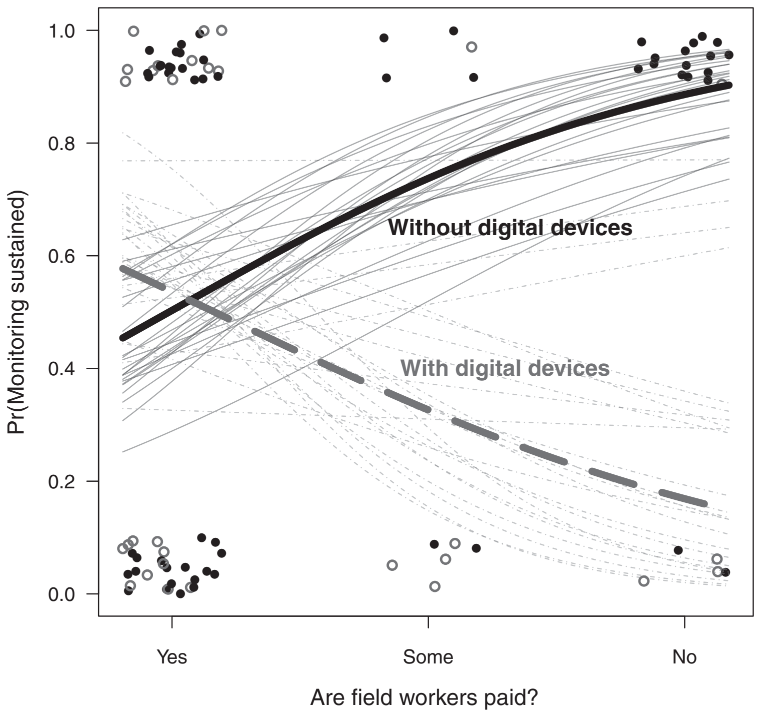


*Figure 4. The probability (*Pr*) of a publication explicitly stating that its monitoring program is ongoing as a function of whether field workers were paid and the use of digital data collection (thick lines, predicted probability derived from the combined public participation and duration and complexity model with all other predictors at their means; thinner lines, 50 simulations of possible models based on estimated model coefficients and their standard errors [Gelman & Hill 2007]; solid circles and lines, programs using digital devices; open circles and dashed lines, projects operating without digital devices). Data points (*n = 84*) were jittered to improve density visualization.*

construction of the Sông Tranh 2 hydroelectric dam, and this fostered distrust between participants and the national government. Participants, including the Tra Bui commune president, reported an interest in protecting the integrity of their forests, but monitoring objectives did not coincide with their economic priorities and increased financial support was required to mitigate lost farming opportunities.

In the Canadian cases, community objectives also appeared not to coincide with those of PM, particularly due to the use of digital data entry. In most communities, suspicion was expressed regarding PM and the use of digital data entry and how these could facilitate the unauthorized access and use of TEK. It was repeatedly expressed that traditional methods of monitoring were sufficient to address local needs. For example, participants said, "Inuit know their land and do no need this technology" [Kangiqsujuaq] and, "The one thing . . . I did not do [or] like is the GPS of the area. . . . others might come around" [Wemindji]. As a result of these suspicions and a lack of collaboratively agreed-upon objectives, these pilot projects had not led to sustained PM.

Although a dearth of broadly accepted monitoring objectives detracted from PM in some contexts, in others the complexity of field protocols may have diminished monitoring sustainability. In Mole National Park (MNP), Ghana, sightings of larger mammals have been recorded since the late 1960s during enforcement patrols of local wildlife guards (Burton 2012). In this type D case, indigenous wildlife guards with little formal education or training collect data for use by park managers and external scientists (Danielsen et al. 2009). In 2006 handheld GPS units were integrated into the monitoring protocol to supplement wildlife sightings with digital records of locations and patrol effort. Simultaneously, the effectiveness of this system was compared with results from a survey with digital camera traps; portions of the survey were implemented by local wildlife guards (Burton 2012). Although patrol surveys had poor detectability of some species, low repeatability of observations, and uneven sampling effort, they were financially and organizationally more sustainable than the camera-trap surveys, which are no longer being operated by wildlife guards in the park. Both GPS and camera traps increased equipment costs, upkeep costs (e.g., batteries, memory cards, unit replacement), and training and technical support requirements, but cameras did so to a greater degree. When deployed properly, camera traps were more capable of reliably detecting mammals, particularly small, nocturnal, carnivorous ones. But wildlife guards had greater success using GPS in the field, and overall the cameras' greater complexity, costs, and technical requirements made them less sustainable in this case. The use of GPSs required less training and oversight, cost less than camera traps, and enabled the quantification of patrol effort for standardizing observations. In this case, the GPS protocol, not the camera traps, was sustained due to its greater operational simplicity.

## Discussion

Our meta-analysis and case studies suggested that the role of digital data entry in PM depends strongly on

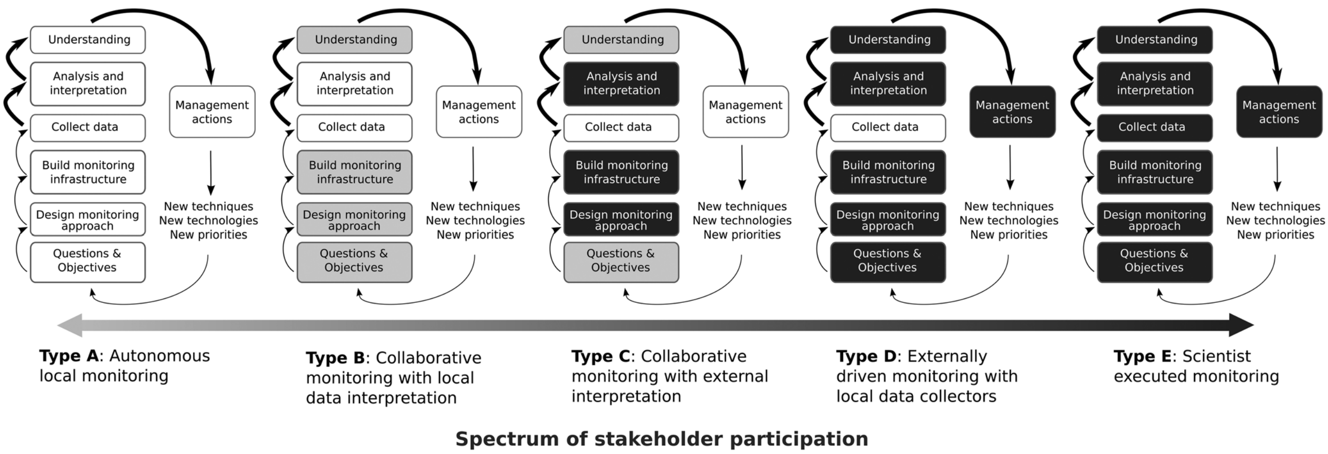


*Figure 5. The participatory adaptive monitoring framework, including a spectrum of stakeholder participation in monitoring approaches (Danielsen et al. 2009, 2014*a*) mapped onto a modified adaptive-monitoring framework (Lindenmayer & Likens 2009). Contributions by government and university scientists external to the local community (e.g., government and university scientists) are indicated by black, local community contributions are in white, and a combination of the 2 in grey. Bold arrows represent instances where digital data entry may facilitate the monitoring process.*

the structure and capacity of the monitoring program and the socioecological context in which it occurs. We found more participatory programs used digital data entry less frequently, similar to monitoring programs focused on specific actions (e.g., opposing development of an electrical generating station) rather than in programs investigating a research question (Wiggins & Crowston 2011). More participatory programs may have less capacity for, or interest in, investing in and supporting technological infrastructure (Olson et al. 2014; Will et al. 2014), and fewer participatory projects may occur in more affluent (e.g., North American, European) societies with relatively easier access to digital technologies. When digital data entry was used, we found ongoing, staff-intensive, participant training and support were important to sustain its use and evolution. In both our literature review and our cases, stakeholder participation and digital data entry were positively associated with management actions, but their relationships with monitoring sustainability were less clear. Participatory monitoring frequently engages local decision makers and can lead to more rapid management interventions at this level (Danielsen et al. 2010). The association of digital data entry and management actions could result from reduced delays between recording observations and reporting results or from the recording of higher quality data that is more useful and compelling for decision makers.

We propose that the advantages and disadvantages of digital data entry in PM can be best understood through Lindenmayer and Likens (2009) adaptive monitoring framework. This general framework states that environmental monitoring is most effective when it incorporates a number of features, including explicit and evolving questions, a clear conceptual model of the ecosystem, statistical design of the sampling protocol, and strong partnerships with policy makers and resource managers (Lindenmayer & Likens 2010). These partnerships are important to ensure that monitoring "passes the test of management relevance" (Lindenmayer & Likens 2010). We propose that, to conduct adaptive monitoring that is participatory, these partnerships must be expanded to include stakeholders like local residents, resource users, and indigenous peoples (Brunet et al. 2016). The role these stakeholders play in the different steps of an adaptive monitoring program will vary (Fig. 5), but their inclusion should ensure that monitoring programs are relevant to scientists, policy makers, and resource users. In this participatory adaptive-monitoring framework, technology is not central to the process of monitoring.

Implemented effectively, technologies like digital data entry allow collection of more data of higher quality by reducing data-entry errors, transcription errors, and processing time; improving the accuracy of location data; and, most importantly, quantifying survey effort (e.g., Inman-Narahari et al. 2010; Olson et al. 2014; Will et al. 2014). These data are subsequently more useful for analysis, interpretation, and decision making. Implemented ineffectively, or in projects where it is unnecessary, digital data entry can be an additional expense whose costs and upkeep distract from core monitoring objectives and undermine a project's long-term sustainability (Lindenmayer & Likens 2010). Implementing innovative technologies is not a determinant of effective environmental monitoring; rather, effective monitoring depends more on collaboratively defined questions and objectives, conceptual models, and monitoring approaches determined through effective partnerships between relevant stakeholders. Digital data entry can frequently improve programs built on these strong foundations, but it is no remedy if these foundations are weak.

In conclusion, our meta-analysis and multiple case-study analyses suggested both stakeholder participation and digital data entry can contribute to environmental monitoring success by linking results and management actions. However, digital data entry can be a detriment to PM sustainability depending on the context and structure of the program. If it engages stakeholders in its design, a PM program can benefit from the advantages of digital data entry (e.g., high data quality). Yet even if the program is amenable, digital data entry may not be necessary. Knowing program objectives, structure, and capacity allows for an explicit weighing of the two-sided implications of digital data entry. For example, technology can engage youth and other technophiles but may discourage technophobes. Whether digital data entry simplifies fieldwork depends on the user, protocol, interface, device, and environmental conditions (e.g., cold, wet, etc.). Digital data can be more easily shared, but it can also be more difficult to keep private, a particular concern when data are sensitive. Digital data entry can increase program capacity to record, standardize, and share observations, but it can also increase the dependency of PM programs on outside technology, expertise, and support (Danielsen et al. 2005; Constantino & Carlos 2012; Funder et al. 2013). Thus, whether digital data entry contributes or detracts from PM depends on factors related to the technology, the organizational structure of the monitoring program, and the socioecological context in which it occurs. In most cases, the appropriate role of digital data entry in PM depends more on the context in which it is used and less on the technology itself.

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## Supporting Information

Detailed descriptions of case studies (Appendix S1); additional figures demonstrating the relationship between program sustainability and levels of participation and project cost (Appendix S2); model selection tables for the use of digital data entry, management actions, and program sustainability (Appendix S3); and the data used in the meta-analysis (Appendix S4) are available online. The authors are solely responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author.

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