

Research article

Sustainable management of non-timber forest products in Peruvian Amazonia: lessons learnt from participatory use of smartphone technology

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ABSTRACT

Over a billion people rely on tropical forest resources for their livelihoods, so sustainable resource use is essential for long-term human and ecosystem health. Smartphone technologies are increasingly proposed as a cost-effective and accessible way of widening community participation in environmental monitoring, but existing studies typically focus on the technological capabilities of smartphones for data collection, rather than how they represent local community interests or affect conservation outcomes. To address this gap, we report on the participatory and technical potential and limitations of smartphone-assisted collaboration for sustainable management of *aguaje* palms (*Mauritia flexuosa*), a commercially valuable species in the Peruvian Amazon. We assessed the potential of smartphone-based data collection, using OpenDataKit (ODK), for monitoring forest resources, working with a community management group and the Peruvian National Service of Natural Protected Areas to quantify and map the distribution, abundance and productivity of *aguaje* palms. Our study highlights tensions between technical and participatory elements of the process. We demonstrate the accessibility of ODK to users with varied levels of digital literacy, its ability to represent multiple interests and the potential to innovatively combine small ODK datasets with vegetation data and Google Earth Engine mapping. However, our work highlights the risk that dependence on digital technologies can exclude stakeholders with poor connectivity, since the process mainly engaged digitally connected partners. Based on this experience, we provide four lessons to support good practice and avoid misalignment of technological and participatory interests in the design and implementation of participatory environmental management using smartphone and open-source technology.

1. Introduction

Tropical forests support high biodiversity (McRae et al., 2017) and are vital for regulating global climate (Mitchard, 2018), as well as providing sources of timber and non-timber forest products (NTFPs)

(Shackleton et al., 2015). NTFPs, which include food products, medicinal plants, construction materials and resin, can provide between 10 % and 60 % of annual household income for people living in or close to forested areas (Shackleton and Pandey, 2014). However, with increasing demand for natural resources and food production, extractive industries

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such as commercial logging and agricultural expansion have become widespread, reducing forest area and quality. Alongside over a billion forest dependent peoples living across the tropics (Lewis et al., 2015), the supply of NTFPs from the remaining forests may be locally over-exploited, increasing the challenge of sustainably meeting the demand for NTFPs.

Greater involvement of local communities is frequently proposed as a way to work towards more equitable outcomes for people and conservation, within and beyond protected areas (Oldekop et al., 2016). Widely available technologies, such as smartphones, are increasingly recommended in conservation as a cost-effective and accessible way of widening community participation in environmental monitoring and management (DeVries et al., 2016; Danielsen et al., 2021; Slough et al., 2021). Indeed, some have suggested that the widescale application of smartphone technology could lead to a fundamental shift in how environmental data is gathered and shared (Jepson and Ladle, 2015). Whilst smartphone ownership is not ubiquitous (Sotomayor-Beltran and Andrade-Arenas, 2019), it is increasing and many of the world's poorest communities are often familiar with smartphone systems (Avle et al., 2018).

However, technology can play an uneasy role in participatory data collection and mapping because it can have negative and unintended consequences (Fox et al., 2006). For instance, although participatory mapping can allow contributors to produce maps that reflect their interests, potentially supporting communities to negotiate for their priorities (Ramirez-Gomez et al., 2016; Robinson et al., 2016), reliance on digital mapping and monitoring can place emphasis on technical rather than ethical or political aspects of mapping and thus entrench exclusion and marginalisation by reinforcing the digital divide (Chapin et al., 2005; Cochran and Corbett, 2020). Existing studies on the use of smartphone technology for community-based monitoring typically focus on the technological capabilities of smartphones for data collection and app development, rather than how it effects representation of local community interests and conservation outcomes (Andrachuk et al., 2019). This highlights a pressing need to assess the potential and pitfalls of smartphone-enabled partnerships in natural resource governance, while continuing to explore the technical capacity of smartphone technology to contribute to forest recording and monitoring.

In this study, we report on lessons we have learnt about the participatory and technical potential and limitations of smartphone-assisted collaboration for sustainable management of NTFPs using a case study from the Northern Peruvian Amazon. We evaluate the capacity of a smartphone data collection tool, Open Data Kit (ODK, <https://opendatakit.org/>), to support the participatory process of revising a community management plan for *Mauritia flexuosa*, a keystone ecological and economic species in Amazonian forested peatlands (Virapongse et al., 2017). ODK is an open-source smartphone software package that can be used to collect data offline, including spatial data using the smartphone's inbuilt GPS (Open Data Kit, 2019).

Renewal of a resource management plan in our study area provided an informative opportunity to evaluate the use of smartphone technology in conservation for several reasons. Firstly, the periodic renewal of the management plan for *M. flexuosa* (locally known as *aguaje*), represents an important point of interaction and negotiation between local communities and the Peruvian National Service of Natural Protected Areas (SERNANP), since the plan is used to inform conservation, regulate community harvesting of *aguaje* fruit and evaluate community requests for changes in harvest quotas, based on economic returns and livelihood needs. Secondly, renewal of 4-year management plans requires periodic inventories of *aguaje* abundance and productivity, but there is no prescribed methodology for undertaking these inventories, which leaves open an opportunity to develop a methodology that is accessible and supports both state and community interests. ODK is well-suited to collecting spatially explicit vegetation data and has previously been used for community-based data collection (e.g. DeVries et al., 2016). Thirdly, there are limited resources and capacity to undertake

these periodic inventories, even though they are a requirement for protected area management in Peru (Naughton-Treves et al., 2006). This generates an opportunity to use relatively low-cost smartphone technology that is adapted to low connectivity in these remote forests, alongside allowing us to evaluate its usability among participants with differing levels of digital literacy. Finally, two unexpected events occurred during the study which required us to adapt how participation was conducted: 1) changes in local leadership reduced community involvement and 2) travel restrictions imposed during the Covid-19 pandemic meant that the planned in person discussion about the process and results had to take place remotely, i.e. online. These events led us to adapt how we implemented data collection and presented the outputs of smartphone and open-source mapping to ensure continued representation of community interests. To this end, our study combines participatory data collection using an open-source smartphone interface with open-source mapping programmes, to address two objectives: (1) we examine the capacity of these tools to support participatory management of NTFPs involving stakeholders with differing priorities, skillsets and levels of authority and digital literacy, and (2) we assess the potential to combine data collected using ODK with formal forest inventory data for mapping NTFP resources.

We evaluate these two objectives using a success/failure approach (Catalano et al., 2019). The terms 'success' and 'failure' are regularly used in the research literature to describe aspects of conservation projects or to evaluate the overall process, and are considered crucial for learning and adaptive management (Armitage et al., 2008; Kretser et al., 2018; Catalano et al., 2019; Chambers et al., 2020). There are no generalised criteria for evaluating success or failure, since evaluation criteria will differ case by case, depending on the situation under consideration. Thus, in our study, we draw on criteria identified in critical reviews of smartphone use in community-based monitoring (Andrachuk et al., 2019) and participatory mapping (Cochran and Corbett, 2020) to evaluate the effectiveness (successes/benefits, failings/limitations) of a smartphone-assisted participatory mapping process at the design, implementation, analysis and communication stages. In doing so, our study identifies critical lessons for the emerging field of technology-aided conservation using smartphones and open-source software, where positive expectations around the potential of technology to support participatory monitoring and conservation have to date received limited evaluation (Andrachuk et al., 2019).

2. Socio-ecological context: balancing conservation and livelihoods through *aguaje* harvesting in the Pacaya Samiria National Reserve, Peruvian Amazon

Our case study area is located within the Pacaya Samiria National Reserve (PSNR) in the Peruvian Amazon and provides an example of long-standing integrated conservation and community-based natural resource management (Kilbane Gockel and Gray, 2009). The PSNR first received protected status in 1940 and covers ~2.1 million ha of wetland ecosystems, including seasonally flooded and peat swamp forests which are home to threatened aquatic species and flooded forest flora and fauna. Approximately 24,000 people live within the PSNR and another 68,000 live within the 10 km wide buffer zone (SERNANP, 2009). These are primarily *riberaño* communities with mixed ethnic origins. Communities that were established prior to the creation of the reserve are legally permitted to reside there and use forest resources according to regulations and limits set within the reserve-wide zonation scheme and resource-specific management plans (Fig. S1).

The ecologically and economically important *aguaje* palm exemplifies the importance of co-management for conservation and livelihoods. *Aguaje* grows in high densities in palm swamp forests, locally known as *aguajales*, which often form on a peat substrate (Draper et al., 2014). Peatland *aguajales* have a high carbon density, >750 Mg C ha⁻¹, which is over three times higher than *terra firme* forest, with approximately 90 % of carbon stored below-ground (Honorio Coronado et al.,

2021). Thus, they represent an important carbon store in Peru, with their significance to the global carbon cycle greatly exceeding their relatively small area (Draper et al., 2014; Hastie et al., 2022). *Aguaje* palms also contribute significantly to local livelihoods and indigenous culture as a source of fibres for weaving and, on a much larger scale, as a source of fruit. Over 260 communities from across the major watersheds in the PSNR and surrounding area are involved in commercial harvesting of *aguaje* fruit (Virapongse et al., 2017). Within the Marañón watershed, which partly covers PSNR, 77 % of households use unsustainable harvesting techniques, felling and thus killing the females of this dioecious species to access the fruit, while only two of 24 communities studied exclusively used more sustainable climbing techniques to harvest the fruit (Romulo et al., 2022). Felling, when carried out intensively and over long periods, alters the structure and species composition of *aguajales* (Manzi and Coomes, 2009), as well as increasing CO₂ emissions from peat through disturbance of the underlying substrate (van Lent et al., 2019). It takes around seven to ten years for juvenile *aguaje* palms to mature and bear fruit (Romulo et al., 2022) and palms are often felled faster than they can regenerate, forcing community members to travel increasing distances to harvest (Schulz et al., 2019; Hidalgo Pizango et al., 2022).

The prevalence of unsustainable harvesting outside PAs and growing economic demand for *aguaje* (Horn et al., 2018) heighten the importance of finding ways to support joint conservation-development efforts. PSNR management plans have consistently encouraged sustainable harvesting of *aguaje* to support conservation and livelihoods. Since 2004, management plans have been co-developed with community members following an increase in the number of community management groups and the passing of national legislation to support participation in natural resource management (Durand and McCaffrey, 1999; Kilbane Gockel and Gray, 2009). Approved *aguaje* management plans are required for legal harvesting of fruit within PAs for commercial sale.

Veinte de Enero, the focus of our study, is a *ribereño* community of approximately 30 families (c. 180 people; Faustino, 2014), located within the PSNR (Fig. 1). They are among the minority of communities that practice sustainable resource management, climbing trees to harvest fruit and planting seedlings near communities to mitigate local depletion (Manzi and Coomes, 2009). *Aguajales* are extensive in this area (Draper et al., 2014) and harvesting *aguaje* is one of the principal economic activities in the community (Kilbane Gockel and Gray, 2009),

with all families generating some of their income from the sale of *aguaje* fruit. The community is located approximately 35 km from the large trading post of Nauta, giving relatively good access to markets (Horn et al., 2018) and their agreed quotas for *aguaje* harvest have increased since 2009, thanks to sustainable harvest methods. However, the income derived from harvesting has remained insufficient to meet the basic economic needs of families (Faustino, 2014). This is because there is currently no price premium for sustainably harvested fruit, so they compete with communities who do not practise sustainable harvesting. In addition, the community consider some locations within the existing *aguaje* management area to be inaccessible. These conditions make Veinte de Enero an ideal area in which to explore the use of open source smartphone technology with low connectivity requirements, specifically ODK (DeVries et al., 2016; Andrachuk et al., 2019; Cochran and Corbett, 2020), to address the shared and differentiated interests of three stakeholder groups: ACORENA – the Association for the Conservation of Natural Resources in the community of Veinte de Enero, SERNANP – representing state interests, and researchers – investigating the social and ecological values associated with peatland ecosystems using methods including participatory mapping and landcover classification (Schulz et al., 2019; Hastie et al., 2022).

3. Research methodology: implementing smartphone-assisted participatory *aguaje* monitoring and mapping

Our methodology combines a qualitative approach to participatory data collection and quantitative methods for assessing ODK inventory data and undertaking mapping of *aguaje* resources using Google Earth Engine (GEE). The case study research methodology comprises three stages: (1) conception and development of a smartphone-based data collection app to support management plan renewal using field-based dialogue and training involving all three stakeholder groups, (2) ODK-enabled data collection, and (3) researcher-led data analysis and mapping. Unexpected events led us to adapt our original study design during the data collection, analysis and communication stages, which is outlined in the research methodology as it forms an integral part of evaluating the potential of smartphone technology for participatory data collection. Analysis of quantitative data is presented in section 4, and evaluation of the success and failures of our participatory data collection approach are presented in section 5.

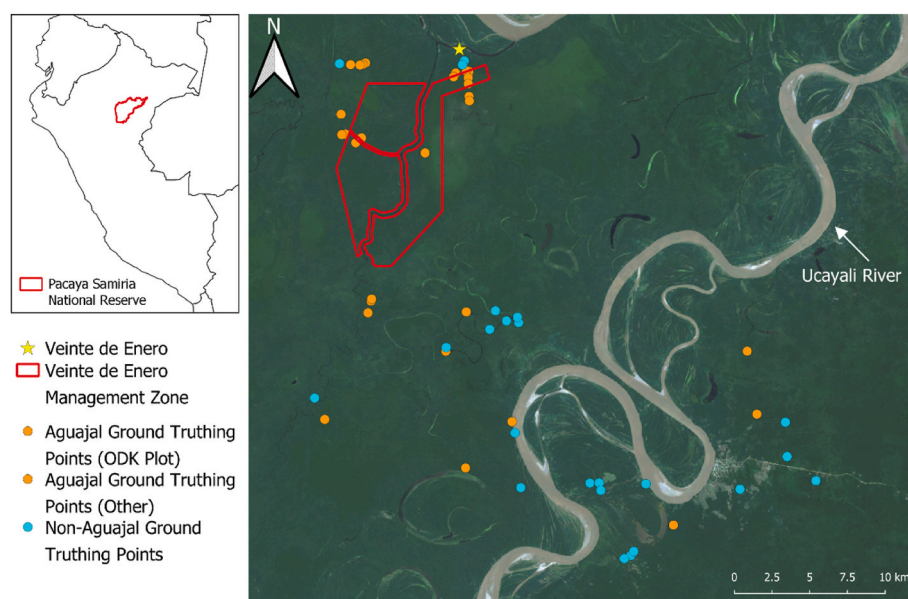


Fig. 1. Locations of PSNR and Veinte de Enero, extent of current *aguaje* management zone, and location of ground truthing points used in mapping. Base layer is Landsat 8 cloud free composite from 2019 showing location of major rivers in relation to the community. (Colour figure).

Each of the three stakeholders (community, state, researchers) had specific priorities, skills and constraints. It was therefore clear from the outset that the role and level of participation of each stakeholder would vary through the process due to the existing hierarchical relationship between the state regulators and the community, and the uneven distribution of digital skills across the three groups (Table 1). Such unequal relationships are a common and challenging feature in the governance of PAs and in technological approaches to participation (Naughton-Treves et al., 2006; Oldekop et al., 2016; Andrachuk et al., 2019). In our case, the task of analysing the smartphone data and producing maps of *aguaje* distribution and abundance lay with researchers because of the need for internet connectivity and specialist skills. While SERNANP staff have GIS skills, ODK was new to them. Poor connectivity and low digital

Table 1

Contribution of different project stakeholders, before, during, and after the field data collection activities. Points in parentheses indicate planned activities that were not possible due to Covid-19 travel restrictions, and points in *italics* indicate modified or additional activities developed to adapt to and mitigate changing circumstances.

Stakeholder Group	Prior to Field Data Collection	During Field Data Collection	After Field Data Collection
ACORENA (Community)	• Work with researchers to develop ODK data collection app • Participate in ODK training • Show researchers <i>aguaje</i> harvest sites suitable for data collection	• (Collect data using ODK app) • <i>Accompanied & assisted students & park rangers during data collection</i>	• (Participate in workshop to discuss results and management implications)
SERNANP (Government Body)	• Participate in ODK training • Discuss <i>aguaje</i> managements plan & data requirements	• <i>Provide logistical support for data collectors</i>	• Use inventory data to develop new management plan • (Participate in workshop to discuss results and management implications) • <i>Discuss potential for revised management areas online with researchers</i> • <i>Carry out preliminary data analysis</i>
University Students & Park Rangers (replacement data collectors)		• <i>Collect and upload data</i>	
Researchers	• Work iteratively with ACORENA & SERNANP to develop ODK app • Lead ODK training with ACORENA & SERNANP	• <i>Provide remote training and technical support to students and rangers working in the field</i>	• Analyse inventory data & produce maps • (Lead & participate in workshop to share results and discuss results with community & SERNANP) • <i>Discuss using virtual methods the potential for revised management areas with SERNANP</i>

literacy precluded the community from direct involvement in the land cover mapping component of the project. The researchers also acted as trainers and facilitators, supporting ACORENA and SERNANP's priorities through the project. Prior informed consent (PIC) was obtained from participants before research commenced.

3.1. Conception and design

When we visited Veinte de Enero in October 2019, the *aguaje* management plan was due for renewal, which required an inventory of resources to review *aguajal* productivity and the current extraction quota. ACORENA consider parts of the existing *aguaje* management area to be relatively inaccessible because they are located far from rivers and trails. This motivated their interest in contributing to the inventory, to review both the location and productivity of the current management area. SERNANP's involvement was motivated by a lack of resources and of a prescribed methodology for undertaking the forest inventory required to update the management plan. Previously, they employed external contractors to conduct these inventories, but they now consider this prohibitively expensive. Additionally, using external contractors further distances the community from decision-making related to their livelihoods. Based on our discussions with ACORENA and SERNANP, we proposed a participatory approach using open-source smartphone technology to allow them to collect the data necessary to review harvest quotas and management areas.

To support our first objective, in person interactions were an early priority for us to build trust with ACORENA and SERNANP, improve the accessibility and acceptability of the smartphone interface (Teacher et al., 2013), and ensure differing priorities were incorporated into the data collection template during the limited time that the researchers had in the field with the community and SERNANP. SERNANP staff responsible for PA management are based in Iquitos, the regional capital, which is several hours from Veinte de Enero, and this also limits opportunities for regular in person interaction.

The ODK toolbox was used to create a smartphone-based data collection app that would allow members of ACORENA to carry out an inventory of *aguaje* abundance and productivity in current and desired harvest areas which are located, respectively, inside and outside the current approved management area. App development was an iterative process led by researchers in consultation with ACORENA and SERNANP. The ODK app and the types of information that can be collected were demonstrated to ACORENA members in the field. ACORENA developed a list of questions that they wanted to include. These were combined with the minimum data requirements for the *aguaje* inventory from SERNANP to create the first version of the ODK app. The final version, used for field data collection, was produced after two further rounds of revisions with ACORENA to ensure that it met all their requirements (Table 2).

ODK inventory plots were selected and laid out with the help of ACORENA who identified locations they used for harvesting (Fig. 1). Nine inventory plots of 0.5 ha (50 × 100 m) were set up in *aguajales* around Veinte de Enero. This made the ODK process compatible with ecological survey methods used previously in the area (e.g. Draper et al., 2014) and allowed us to explore the potential to combine small, ODK-generated inventory datasets with existing forest plot data (objective 2; Table S1), which provide the ground reference data necessary for landcover classification and mapping of ecosystems in the wider Pastaza-Marañón Basin (Rainfor, 2009; Honorio Coronado et al., 2021; Hastie et al., 2022).

To build familiarity with participatory use of smartphone tools, six members of ACORENA and one SERNANP representative were trained to use the ODK app (Fig. 2). In person training was conducted in the field, with data collection practiced in one of the inventory plots. Each trainee had access to a smartphone during the half-day training session and three ODK-enabled smartphones were left with ACORENA to complete the inventory. ODK app development and the selection of

Table 2

Questions used in the ODK app. Instructions were as follows: Answer question 1 once per plot. Answer questions 2–5 for every individual *aguaje* stem in plot. Data User indicates which participant group wanted this data to be included in the ODK app: 1 = ACORENA, 2 = SERNANP, 3 = Researchers. The variety of *aguaje* (number 5.3.2) determines the use and price of the fruit. Questions were presented in Spanish in app. Options for questions 1 & 5.3.2 are local names for zones & *aguaje* varieties.

Number	Criteria	Question	Options	Data Type	Notes	Data User
1		Which Aguaje Management Zone is the plot in?	Existing Management Zone: Paima/31 Diablos/Paujil New Management Zone: Victoria/Moico/Cetico Poza/Flores/Villa/Chambira/Iricahua/Other	Multiple choice	Answer question 1, once per plot	1,2
2		Take GPS point of location of aguaje stem		GPS Coordinate in Decimal degrees	Minimum accuracy threshold set to 15m	2,3
3		What is the stem diameter (cm)?		Numerical	Measured using DBH Tape	2,3
4		What is the height (m)?		Numerical		2,3
5		What sex is the aguaje?	Male/Female/Juvenile	Multiple choice	If 5 = Male; no more questions, go to next aguaje stem in plot and return to Question 2	1,2,3
5.1	If 5 = Juvenile	What sex is the juvenile aguaje?	Male/Female/Don't Know	Multiple choice	No more questions, go to next aguaje stem in plot and return to Question 2	2,3
5.2	If 5 = Female	Are there flowers or fruit?	Flowers/Fruit	Multiple choice		1,2
5.2.1	If 5.2 = Flower	How many flower bunches?		Numerical	No more questions, go to next aguaje stem in plot and return to Question 2	1,2,3
5.3.1	If 5.2 = Fruit	How many fruit bunches?		Numerical		1,2,3
5.3.2	If 5.2 = Fruit	Which variety is the fruit?	Shambo/Shambo Azul/Amarillo/Color/Huira Aguaje/Posheco	Multiple choice		1
5.3.3	If 5.2 = Fruit	What size are the fruit?	Small/Medium/Large	Multiple choice	No more questions, go to next aguaje stem in plot and return to Question 2	1



Fig. 2. ODK field training involving researchers and members of ACORENA and SERNANP. (Credit: left – L. Cole; right – C. Wheeler).

inventory plots took place over a period of 10 days in October 2019.

3.2. Data collection

Members of ACORENA planned to undertake the ODK-based smartphone inventory between October and December 2019. However, during this period, a new president assumed leadership of ACORENA, replacing the previous incumbent who had been involved in developing the ODK app, organising training and facilitating an early phase of data collection. This change of management altered the organisation's role in the inventory from one of leadership to provision of assistance in data collection, since the new president was less directly engaged with the researchers and had different priorities. To ensure data collection could proceed we, with the help of SERNANP and research partners at the Instituto de Investigaciones de la Amazonía Peruana (IIAP), recruited a group of students with ecological field experience from the local Universidad Nacional de la Amazonía Peruana (UNAP). Training in the use of the ODK app was provided remotely to student data collectors since researchers were not able to return to Peru and the students were well-placed to learn digitally. The students were assisted in the field by

ACORENA representatives and locally based SERNANP park rangers.

Five of the established plots were surveyed in March 2020 using the ODK app to record the survey data (see Table 2). Plot boundaries were delimited with string, markers were placed every 25 m along the plot edge and their GPS coordinates were recorded. The GPS co-ordinates, diameter at breast height (DBH; 1.3 m above the ground), whether the individual is juvenile (juveniles are defined as *aguaje* stems ≥ 1.3 m in height, which have not yet begun fruiting or flowering), and the sex (male or female, assessed on basis of presence of fruit/flowers as an indicator of degradation, see section 3.3.1) were recorded for each *aguaje* stem. If a stem was female, the presence or absence of flowers or fruit was noted, for fruiting females the number of fruit bunches, fruit variety (*Shambo*, *Shambo Azul*, *Amarillo*, *Color*, *Huira Aguaje*, *Posheco*) and fruit size was estimated (small, medium, large), with help from ACORENA representatives. The variety and size of fruits are related to fruit quality with some varieties achieving a higher price (*Shambo*, *Shambo Azul*). Our methods are consistent with standard forest census protocols (Rainfor, 2009).

The data were uploaded to an online web server when the students returned to Iquitos. The research team then had access to the data and

carried out the analyses. The remaining four plots were not inventoried due to time constraints and COVID-19 related travel restrictions in Peru prevented the students from returning to Veinte de Enero, but they were used as ground reference points in the landcover classification as the forest type and precise locations were known.

3.3. Data analysis and mapping

Data analysis and map production were conducted by the researchers to provide the data related to *Aguafe* productivity and abundance required for management plan renewal, demonstrate GEE methods to SERNANP, and explore the potential to combine local plot inventories with wider datasets. GEE mapping outputs and PSNR zonation data (Fig. S1) were also used to develop alternative management scenarios to support online communication between SERNANP and the researchers and counter the loss of community involvement after the template design and data collection phases.

3.3.1. Forest plot inventory data

In line with the requirements of the management plan inventory, the data collected in the ODK plots were used to establish three key characteristics of the vegetation in each plot: (1) *aguaje* palm density (stems ha^{-1}) estimated for male, female and juvenile stems; (2) *aguaje* fruit productivity estimated from the mean number of fruit-bearing racemes per female stem; and (3) the level of palm swamp degradation assessed using the sex ratio (male:female) of mature *aguaje* palms. The sex ratio of *aguaje* palms is considered to be a good indicator of the condition of the forest since undisturbed stands have a ratio of approximately 1:1 male to female stems (Freitas Alvarado et al., 2019), whereas in more heavily exploited forest – where fruits have been harvested through felling – the ratio is skewed towards males (Manzi and Coomes, 2009).

3.3.2. *Aguafe* classification mapping

We conducted landcover classification to quantify the extent of *aguajales* in and around the current harvest zone to explore how open-source methods can be used to combine smartphone-based plot inventories with wider ecological datasets (objective 2). Outputs were presented to SERNANP to demonstrate how ODK tools can support natural resource management. In turn, SERNANP supported mapping by sharing shapefiles for the harvest area and the park-wide zonation which defines permitted uses.

We used a Random Forest (RF) machine-learning algorithm, executed in GEE, to map the distribution of *aguaje* forest. The ODK plot data were used in combination with forest plot data from the region (Fig. 1, Table S1) to train the algorithm. Data from 32 forest plots (combined area = 19.6 ha) from *aguaje* forest, and 21 plots (combined area = 15.7 ha) from non-*aguaje* (i.e. seasonally flooded and *terra firme* forest) were used in the classification and validation (Table S1). Mapping was conducted at 20 m resolution for an area encompassing the current *aguaje* management area plus areas where the community wished to expand their harvesting activities, covering 60,423 ha. Further details of the land cover classification mapping are available in the supplementary information and Table S3.

3.3.3. Supporting management: inventory reporting and scenario mapping

Pandemic-related travel restrictions prevented in person presentation and discussion of the ODK inventory and mapping results. Instead, discussions between SERNANP and the research team took place via video calls in which we presented the inventory and landcover results. Poor phone and internet connectivity and continued restrictions on travel within Peru prevented community involvement in video discussions. To partially mitigate the limited community involvement in the data collection, analysis and dissemination phases, we developed alternative harvesting scenarios that incorporated their concerns. ACORENA explained at the outset that, from their perspective, the existing management plan gave an inflated impression of the available

harvestable area because some parts of it were inaccessible. *Aguafe* fruit is typically harvested in accessible locations along rivers and well-established trails (Delgado-Aguilar et al., 2017) and ACORENA stated that harvesters rarely travel further than 1 km into the forest from these access routes.

Scenarios analysis combined ODK inventory data with the landcover classification map and were informed by the PSNR zonation scheme (Table S1) and landscape characteristics which determine the accessibility of potential harvest areas, as identified by community members. This allowed us to explore innovative ways of combining smartphone data with ecological data to support participatory management, thus contributing to both study objectives. The estimates of *aguaje* distribution (derived from landcover classification), and the number of female trees (a proxy for fruiting density, derived from the inventory) in the current management area were compared for three alternative harvest area scenarios, each with differing boundaries. Female palm abundance for each scenario was calculated using mean female stem density and area estimated in each scenario.

In scenario 1, the ‘current accessibility scenario’, a 1 km buffer was placed along access routes and delimited by the current management area boundary to estimate the area currently accessible for harvest. Scenario 2, the ‘current zonation scenario’, also consists of a 1 km buffer along access routes, extending beyond the current management area boundary but, respecting the national reserve zonation in place in 2019, it was clipped at the boundary between the extraction zone and the strict protection zone (Fig. 3a). Scenario 3, the ‘community-modified scenario’, uses a 1 km buffer along access routes and includes potential harvest locations identified by the community which lie outside the current management area boundary, but does not take into account national reserve zonation, instead extending into the strict protection zone. For each scenario, we estimated the area of *aguaje* forest and the number of fruiting palms by scaling the inventory estimates of female stem density by area (Table, Table S2). These were presented in the online discussions about management planning.

4. Results: ODK inventory and classification mapping

From our ODK *aguaje* inventory plots we found a mean *aguaje* density of 165 stems ha^{-1} (± 90.4 95 % confidence interval; Table S2). Plots had more male (90.1 stems ± 45.5) than female stems (50.0 ± 18.2) on average, with a mean ratio of 1.9 (± 0.8). In areas that the community identified as historically subject to more frequent harvesting, the ratio was higher, up to 3.2 males for each female stem (Table S2). A male bias in the sex ratio thus appears to correspond with areas that experienced more intensive extraction by felling, before climbing began to be used routinely to harvest fruit between 1999 and 2009 (Durand and McCaffrey, 1999; Kilbane Gockel and Gray, 2009). The inventory plots showed signs of regeneration, with an average of 25 juvenile stems ha^{-1} (± 31.6), although this was highly variable. During the inventory (March 2020), 89 % of female stems were fruiting, with an average of 3.7 (± 0.3) fruit-bearing racemes per stem, which is equivalent to approximately 2.8 sacks of *aguaje* per tree (1 raceme ~ 0.75 sacks of *aguaje*; Faustino, 2014). Compared with the 2014–2019 management plan (Faustino, 2014), these inventory data show a 26 % rise in total estimated production, due to increases in harvestable female palms and fruiting racemes per hectare. The ODK data thus support both participatory management planning (objective 1) and ecological monitoring (objective 2). The combination of ODK plot data with existing plot data from the study area (Table S1) produces a landcover classification map (Fig. 3b) showing the distribution of *aguajales*. This map had a high overall accuracy of 99.5 % and a Kappa score of 98 %; this indicates the proportion of the map that was classified correctly (Table S4). The accuracy of classification of different forest classes was also high, with a user's and producer's accuracy > 97 % for all classes. Based on this classification, the current management area consists of 31 % (1974 ha) *aguaje* forest, a slightly higher proportion than occurs in the wider study

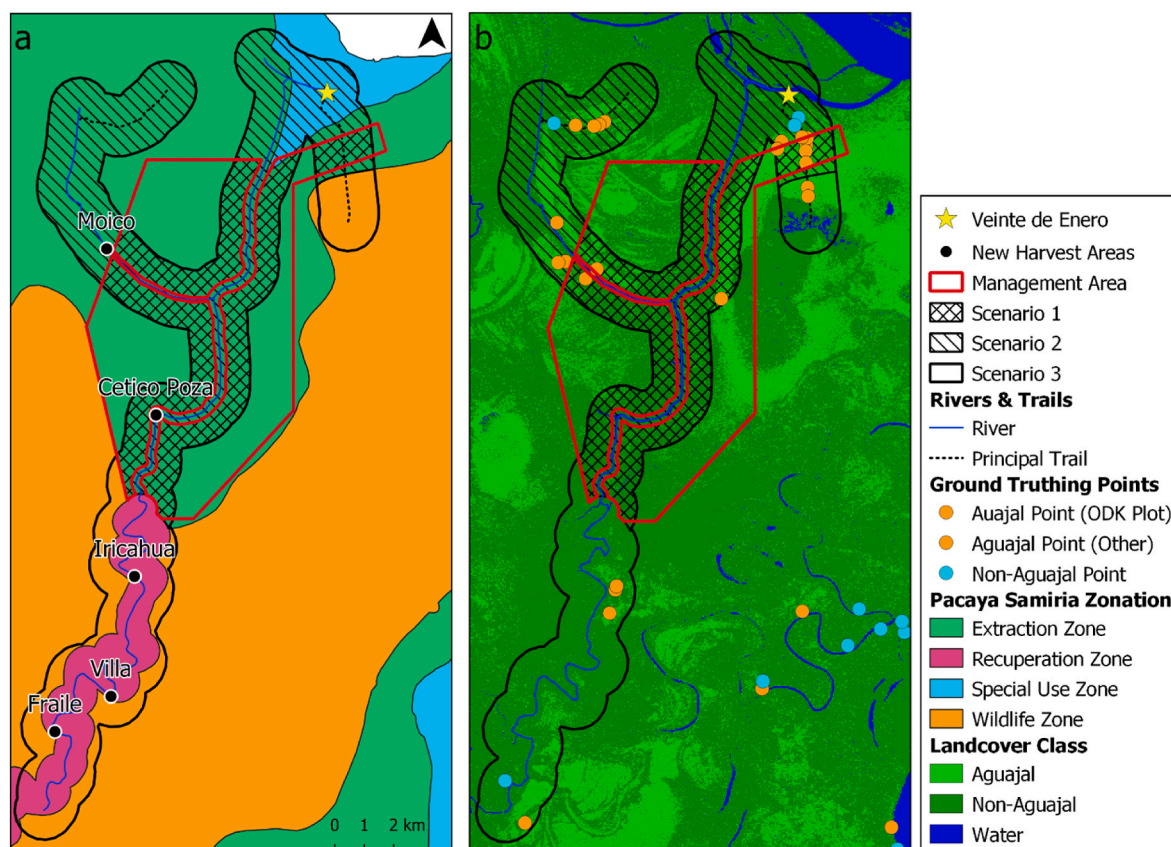


Fig. 3. (a) Alternative management area scenarios and (b) Landcover classification showing distribution of *aguajal* and non-*aguajal* forest types in the study area. The current *aguaje* management area (red outline), the location of potential new harvest areas (black points), and the locations of ground truthing points in *aguajal* (orange shaded points) and non-*aguajal* (blue points) are shown. The three management scenarios are scenario 1 - 'current accessibility scenario' (cross hashed area), scenario 2 - 'current zonation scenario' (diagonal hashed area), scenario 3 - 'community-modified scenario' (thick black line). Harvesting of resources is only permitted in extraction and special use zones. (Colour figure).

area, which had 27 % *aguajal* forest (Table 4).

Using our *aguajal* classification map with our different management scenarios enabled us to quantify the accessibility of available *aguaje* resources. Under scenario 1 (Fig. 3), there was a total of 802 ha of harvestable *aguajal* forest, which represents 41 % of the total *aguajal* forest area within the current management area and contains an estimated 40,100 female *aguaje* palms ($\pm 14,577$; Table 4). In Scenario 2, 1615 ha of *aguajal* forest would be available for harvesting, double the area available in scenario 1 (Table 4). In scenario 3, which considers both accessibility and potential new harvesting areas identified by Acorena, the area of *aguajal* forest available would be 2188 ha, containing approximately 109,400 female *aguaje* palms ($\pm 39,769$). This is a small increase relative to the total area of *aguajal* forest in the current management area (1974 ha), however, as only 41 % of the *aguajal* forest area is considered accessible for harvesting, scenario 3 equates to a much larger area available for harvesting by the community. The influence of these results on management planning is considered below, as part of our evaluation of the use of smartphone and open-source technology on the management of NTFPs.

5. Successes, failures, and lessons learned for participatory smartphone-assisted environmental monitoring

Technology is likely to play an increasing role in conservation and sustainable natural resource management, alongside the need to support local expertise and capacity-building to decolonise science and reduce the impacts of research travel on climate change (Bates et al., 2021, Thurstan et al., 2021). Drawing on critical reviews of smartphone-assisted management (Andrachuk et al., 2019) and

participatory mapping (Cochrane and Corbett, 2020), we evaluate the successes and limitations of our approach using the following criteria: usability and transparency (representation, accessibility, training), power (level of participation, ownership, empowerment), cost-effectiveness, and impacts and outcomes. Objective 1, the capacity of smartphone tools to support participatory management of NTFPs, is the focus of evaluation, while objective 2, the potential to combine small smartphone datasets with formal forest monitoring protocols, is considered primarily under impacts and outcomes. The potential for ODK to support both objectives is considered amongst the four lessons that we then identify to inform future studies.

5.1. Usability and transparency

The early involvement of app users, particularly in the design stage, can result in stronger engagement (Danielsen et al., 2021) and improve the usefulness of apps (Teacher et al., 2013), yet intended users are seldom consulted during app development (Andrachuk et al., 2019). We found that the ODK template could be successfully used to help build trust because it provides a transparent format for discussing and representing stakeholder interests during the design of a data collection template. Trust, representation and transparency are further improved if the template is developed iteratively to explicitly identify and incorporate the shared and separate interests of multiple stakeholders. This approach not only allowed us to identify key harvesting constraints perceived by the community, which informed subsequent scenario mapping, it also has the potential to reassure participants who are not directly involved in all stages of data collection and analysis and is especially important when management decisions are hierarchical.

The ODK template proved accessible for stakeholders with differing levels of digital literacy, using basic community familiarity with mobile phones supported by in-field training to develop and pilot the template. It also proved to be readily useable by an alternative group of smartphone-literate data collectors after the community opted to support rather than lead data collection. This required a shift from in person to remote training to support the replacement data collectors. These two training methods offered different advantages and constraints (Table 3). While the offline functionality of ODK for data collection makes it an effective tool for collecting field data in areas with minimal or no phone signal, limited connectivity can restrict the provision of remote support and troubleshooting, which can undermine both general usability and data quality. Our study demonstrated that it is possible to provide effective training and support both in person and digitally. From our experience, we consider field training a necessity for community involvement in areas like Veinte de Enero where the mobile phone signal is weak, whereas online and text message support in the field is effective with smartphone-literate users, provided that queries can be addressed prior to data collection, ideally through real-time video calls. We present our training outline (Table 3) and step-by-step remote instruction manual (see supplementary materials) as a model for future studies.

5.2. Power, ownership and empowerment

Community involvement in natural resource management has for some time been suggested as a means to shift the balance of power, and to empower participants (Danielsen et al., 2009). However, uneven levels of participation were a pre-determined feature of our study because of differing digital access and literacy between researchers, SERNANP and ACORENA. Inequality was also reinforced by events, which reduced community participation and prevented joint discussion of the inventory data and maps. From a community perspective, our project thus reinforced the digital divide and the unequal distribution of power that already exists in PA governance.

Although such issues impose a major constraint on where and when ODK can support empowerment, it is important to recognise that some participants may see mapping as a short-term problem-solving tool, not

Table 4

Area (ha) of *aguajal* and non-*aguajal* forest, and the number of *aguaje* stems predicted for the whole study area, the current management area, and for each of the three proposed management scenarios. Percentage of total area is given in parenthesis.

Areas	Area (ha)	<i>Aguajal</i> area (ha)	Non- <i>Aguajal</i> area (ha)	No. of <i>aguaje</i> stems	No. of female <i>aguaje</i> stems
Study Area	60,423	16,463 (27.2)	43,960 (72.8)	2,717,493	823,150
Management area	6433	1974 (30.7)	4460 (69.3)	325,842	98,700
Scenario 1	3009	802 (26.7)	2207 (73.3)	132,383	40,100
Scenario 2	6570	1615 (24.6)	4955 (75.4)	266,583	80,750
Scenario 3	10,001	2188 (21.9)	7813 (78.1)	361,166	109,400

a means to lasting empowerment, particularly if priorities between different actors are not aligned. In our case, community access to natural resources is constrained by state regulations because they live within a national reserve. As a result, the local community may have prioritised the opportunity to improve their income derived from *aguaje* by influencing data collection, rather than seeking longer-term data ownership or mapping skills. In contrast, our offer to facilitate an ODK-based inventory as part of a funded research project represented a problem-solving opportunity for SERNANP and was well-aligned with their responsibility for instigating the inventory process. Differing stakeholder objectives do not undermine the value of geospatial technology as part of participatory environmental management, but expectations of lasting impact should be tempered with knowledge of lived realities and weaknesses in current governance systems (Schleicher et al., 2019).

Despite these issues, power can at times leverage positive impacts. Multi-stakeholder partnerships often require a flexible approach to cope with changing circumstances (Bennett and Satterfield, 2018) and the involvement of a locally networked organisation in our study improved

Table 3

Details of the types of training provided in our case study, including the technical requirements, advantages, disadvantages and suitability for each method.

Training Type	Requirements	Advantages	Disadvantages	Participant suitability
In person – field-based + verbal	• ODK Enabled smartphone (provided by trainers) • Availability of participants to attend training	• Participants can use technology in field setting • Ample time to practice using ODK app and ask questions	• Participants must be available for training & based locally • Limited means to address questions or issues that arise after training • Participants may forget method if there is a gap between training and data collection	• Local community • Locally based representatives of government bodies
In person – field-based + manuals	• ODK Enabled smartphone (provided by trainers) • Availability of participants to attend training • Printer (to produce hard copies of manual)	• Participants can use technology in field setting • Ample time to practice using ODK app and ask questions • Manual provides back-up & can be referred to if errors occur or participants forget any elements of the ODK app use	• Participants must be available for training & be based locally • Some unforeseen problems may not be included in the manual, with limited means to resolve the issue	• Local community • Locally based representatives of government bodies
Remote – video call	• Stable internet connection + computer • ODK Enabled smartphone (provided by trainee) • Availability of participants to attend training	• Allows participation from multiple locations and multiple organisations • Allows participants to ask trainers questions directly	• Technology requirement excludes local communities with poor phone/internet connectivity • If questions arise after training there is limited means to resolve the issue	• Representatives of government bodies (based in multiple locations) • Students or other interested parties (e.g. NGOs, other researchers)
Remote – training manual + email support	• Stable internet connection + computer to access resources • ODK Enabled smartphone (provided by trainee)	• Allows participation from multiple locations and multiple organisations • Manual provides permanent record of instructions for use of ODK app • Allows participants to ask trainers questions over email	• Technology requirement excludes local communities with poor phone/internet connectivity	• Representatives of government bodies (based in multiple locations) • Students or other interested parties

our ability to involve alternative data collectors in a timely manner, i.e. by drawing on SERNANP's wider networks (Folke et al., 2005). Applying ODK mapping within a stakeholder network rather than with a single community can thus make it more resilient and responsive to changes in participant availability, thus presenting a pragmatic response to reduced community participation.

5.3. Cost-effectiveness

As recognised by Andrachuk et al. (2019), participatory environmental management studies often comment on the cost-effectiveness of using local expertise and off-the-shelf technology, relative to trained external 'experts' and specialist or bespoke technology (Hahn et al., 2022), but they seldom present or evaluate costs. Our study emphasises that, while smartphones and data plans may be relatively cheap, a focus on technological costs downplays significant and uneven opportunity costs for participants, and support needs for smartphone-assisted resource monitoring. Uncertain longer-term benefits (e.g. a change in harvest area or quota) should not be presumed to outweigh shorter-term opportunity costs of participation by local communities (e.g. reduced availability for daily or seasonal tasks that generate an income, support subsistence or contribute to family responsibilities). In addition, technical and facilitation skills are needed to support processes, like periodic inventories, that lie outside routine natural resource management, especially if these are largely driven by non-local governance institutions (Davies and White, 2012). This highlights the importance of documenting and sharing resources like our ODK training manual to reduce learning costs for future applications.

5.4. Outcomes and impacts

A striking feature of literature on the effectiveness of smartphone-based environmental monitoring is the lack of reporting of outcomes (Andrachuk et al., 2019). This issue is widely recognised in participatory environmental management, where evaluation has focused on the process rather than the outcomes due to the challenges of selecting suitable criteria and the timeframes required (Blackstock et al., 2007; Reed, 2008). We report both short-term successes and failings.

Among the project outcomes, the ODK inventory results were used in the 2021–2026 *aguaje* management plan (Grupos organizados de la Cuenca Yanayacu Pucate – RNPS, 2021). The ODK inventory data represent an improvement on data presented in the previous management plan (Faustino, 2014) in that they include estimates of female palm productivity for different zones in the management area with uncertainty estimates, rather than a single estimate across the entire management area. The inclusion of uncertainty allows for more robust assessments of changes in *aguaje* abundance and productivity if maintained in subsequent inventories. The 26 % estimated increase in *aguaje* productivity since the 2014–2019 management period led to a 29 % increase in the community's harvest quota in the current management plan set by SERNANP. ACORENA's motivation to participate in data collection was to incorporate additional harvest areas into the new management plan. Whilst this was not achieved, higher harvest quotas were set, meaning they have legal access to greater resources, which partially addresses the needs of the community. Additionally, SERNANP supported the ODK process as a means of achieving their legally mandated objectives for renewing the *aguaje* management plan, but in doing so they identified potential longer-term benefits of adopting ODK and GEE tools to help them achieve their objectives in other PAs. These represent instrumental and capacity building impacts.

Despite the less-demanding data collection protocol in this study compared with formal forest monitoring protocols (e.g. Rainfor, 2009), the high accuracy of landcover classification outputs demonstrates that small ODK datasets can be successfully integrated with formal monitoring data and satellite-based datasets using GEE to produce maps and estimates of forest composition, and to support forest monitoring to

track the sustainability of management (Hidalgo Pizango et al., 2022). Pandemic travel restrictions also prompted us to explore the technical capability of ODK and landcover classification, via a set of alternative management scenarios, to represent the interests of digitally excluded local participants. These show that ODK has the potential to represent varied interests, including livelihood and conservation concerns, and our ODK-enabled scenario development expands the repertoire of potential ODK uses in environmental management (Peterson et al., 2003).

Nevertheless, there are significant gaps in our evaluation, in particular, we are unable to evaluate community satisfaction with the process or management plan outcomes. The scenarios were informed by discussions with the community, but they were not co-developed. The harvest area remains unchanged, so our involvement helped set increased quotas but the alternative scenarios did not influence the new management plan. We do not know whether the higher quota is a consequence of sustainable management or a result of the change in inventory method, or whether the apparent increase in productivity and quotas offsets the accessibility issues identified by the community in initial discussions.

5.5. Lessons for choosing smartphone-based tools to support participation and monitoring

Overall, our study demonstrated successes, such as the accessibility of ODK to users with varied levels of digital literacy, its technical suitability for gathering data in remote areas to represent multiple interests and for innovative use of small datasets in combination with existing vegetation data and open-source mapping capabilities. However, it highlights the risk that dependence on digital technologies can exclude stakeholders with poor connectivity, since the process generated very uneven levels of stakeholder participation and mainly engaged digitally connected partners. These experiences allow us to identify four lessons to help avoid misalignment of specialist and community interests in future technology-assisted conservation and community-based monitoring.

Firstly, smartphone-assisted participation is likely to be more equitable and enabling when used with communities that already have reasonable mobile phone connectivity and digital familiarity (e.g. Mena et al., 2020), or as part of an externally supported process (Danielsen et al., 2009). The reasons why ODK is useful (i.e. its ability to collect and store data where internet connectivity is poor) mean that data processing often needs to be done away from the data collection site. Therefore, it is unlikely to increase participation or empower remote communities with limited digital infrastructure, and may perpetuate an extractive approach, where local input is confined to data collection (Rambaldi et al., 2006). In such circumstances, innovations like participatory scenario planning based on ODK and GEE mapping could be used as part of facilitated discussions about the trade-offs between livelihoods and conservation, where maps can be presented in digital or printed format. This has potential to alleviate some inequalities arising from the digital divide, but needs full evaluation and, where there is uneven division of power, it depends on the willingness of the main decision-maker to respond to dialogue.

Secondly, designing the ODK software interface (e.g. data collection template) is a critical stage for building trust and ensuring transparency over whose interests are being represented and how. We recommend an iterative design process to help stakeholders become familiar with the technology and the ways in which it will be used to represent their interests, especially if this is the main point of involvement for local participants. Data ownership and data-led decision-making should also be discussed at the design stage, as part of obtaining research permits and PIC.

Thirdly, to establish whether smartphone technology is a suitable tool, the ability to provide accessible and flexible in person and online support needs to be considered early on in a project. Understanding suitable support tools is particularly important when a study involves

remote locations, where diverse/indigenous languages are spoken or where there are geographically distant partners with differing levels of digital literacy. We recommend involving a partner with strong links to local institutions to improve adaptive capacity in case of technology failures and changes in participant availability, to support data uploading and to avoid overreliance on digital communication, which limited community involvement. However, we recognise that involving local partners often relies on existing relationships and maintains existing power dynamics, which may include unequal decision-making power.

Finally, in relation to our second objective, there is significant technical potential to combine small-scale datasets, like our *aguaje* inventory plots, with the broader mapping capacities available in GEE by combining small ODK datasets with plot data from formal forest monitoring, or if larger ODK datasets are collected. Areas like Veinte de Enero, where the focus has been on sustainable harvesting for over a decade, are scarce, so our understanding of the intersection of forest use and conservation (Garnett et al., 2018) can be improved by integrating ODK-based inventories with formal ecological monitoring data. Recent amendments to Peruvian laws that reduce constraints on forest exploitation and development highlight the need to leverage such data to monitor and support sustainable management and the communities and agencies responsible for this stewardship.

6. Conclusions

Smartphone and geospatial technologies are increasingly used in natural resource management and monitoring, but critical evaluation of what works and when is lacking. We demonstrate that smartphone-enabled ODK can be effective in representing the interests of multiple stakeholders, is accessible to users with differing levels of digital familiarity and can be combined with formal ecological datasets to produce innovative management support tools, like scenario analysis, and generate more robust resource inventories. However, our experience also highlights tensions between technical and participatory elements of the process. Currently, the main challenge lies not in the capacity of smartphone technologies like ODK to collect data, but in aligning and adapting the interests of technologically literate research community to support the issues facing place-based stakeholders. Like all participatory monitoring and mapping, ODK is only as effective as the stakeholder relations and environmental management processes within which it is embedded, and we emphasise the importance of prioritising participation over technology when deciding if and how open-source smartphone and geospatial technology can best support sustainable environmental management.

CRedit authorship contribution statement

Charlotte E. Wheeler: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Althea L. Davies:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Conceptualization. **Luis Andueza:** Writing – review & editing, Investigation. **Lydia E.S. Cole:** Writing – review & editing, Investigation. **Nállarett Dávila:** Investigation. **Jhon Del Águila:** Writing – review & editing, Data curation. **Margarita del Águila Villacorta:** Writing – review & editing, Investigation. **Frederick C. Draper:** Writing – review & editing, Data curation. **Charlotte L.D. Evans:** Writing – review & editing, Data curation. **Eurídice N. Honorio Coronado:** Writing – review & editing, Project administration, Data curation. **Nina Laurie:** Writing – review & editing, Project administration. **Eva Loja:** Writing – review & editing, Resources. **Manuel Martín Brañas:** Writing – review & editing, Investigation. **Edward T.A. Mitchard:** Writing – review & editing, Supervision, Funding acquisition. **Katherine H. Roucoux:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jenvman.2025.126198>.

Data availability

Data will be made available on request.

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