Who Breathes the Smoke? Technologies for Community-Based Natural Resource Management

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ABSTRACT

While technologists have investigated environmental sustainability and conservation problems from a variety of angles, rural communities who manage natural resources have underexplored opportunities to benefit from new technologies. Many rural, Indigenous, and non-industrialized communities around the world have developed mature environmental governance structures and practiced effective resource management for thousands of years, and western environmental studies are increasingly recognizing the importance of social, cultural, and institutional factors.

To date, technologists' engagement with community-based environmental management has been sparse for reasons including cultural differences between rural resource managers and urban technologists, underdevelopment of participant-led research methods, and the up-front investment needed to deploy technologies in remote and low-income settings. We argue that the time is ripe for engagement between technologists and community-based resource management institutions, and use we Elinor Ostrom's design principals for common resource governance to suggest potential technology applications: such as defining and communicating about resource boundaries, mutual monitoring among resource users, and social capacity building. To achieve the best environmental outcomes, technologists need to adopt participant-led research methods that leverage local communities' expertise about their own environments, social institutions, and cultural norms.

CCS CONCEPTS

• **Human-centered computing** → *Computer supported cooperative work*; • **Applied computing** → *Economics*; *E-government*.

KEYWORDS

conservation technology, environmental justice, political ecology, natural resource management, governance

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1 INTRODUCTION

> *Indeed, this is a good example of the difference between living with the results of management, as Indians do, instead of viewing it from afar and theoretically. If tribes accept prescribed fire to improve the conditions of their forest, they get to breathe the smoke.*
>
> John Gordon et. al. [38]

The Tragedy of the Commons is one of the most popular ideas for reasoning about environmental conservation in academic circles. It posits that individuals who share a common resource will destroy the resource by selfishly acting in their own best interests [42]. For decades the *tragedy* model has influenced western environmental thinking, policy, and technology efforts: the perception of communities' inability to sustainably manage a common resource has been cited to prescribe the need for an external enforcer to protect the resource, such as privatization of the resource or top-down enforcement by a governmental agency [57].

The disappointing outcomes of many top-down conservation projects, though, have slowly and gradually brought attention to the critical importance of neglected factors, like economics, culture, and institutions [11]. A well-studied example is the frequent failure of externally imposed fishing bans in marine protected areas [22]—often unenforceable because local small-scale fishers have no alternative sources of income—which has prompted the development of more holistic, cultural-socioeconomic approaches to sustainable fisheries [35]. Newer waves of environmental discourse, like *environmental justice* and *political ecology*, confront the unfair distribution of harms imposed by environmental degradation and the unfair shared costs created by conservation programs, which are frequently borne by communities who face other forms of discrimination [43, 63, 68].

In the 1980's, Elinor Ostrom spearheaded an alternative body of economic and anthropological work that brought to light many cases where communities had, in fact, successfully cooperated to manage common resources without external enforcement by a firm or state. Ostrom's landmark 1990 work, *Governing the Commons* [57], lays a theoretical foundation and devises principles for successful community-based resource management by examining successes and failures in case studies, vital work awarded the 2009 Nobel prize in economics [58]. Communities who heavily depend on a natural resource for their sustenance, like fishers or farmers, are often highly motivated to conserve the resource to protect their own livelihoods. This is a key advantage of community-based management approaches, as documented by Ostrom. Local institutions can also bring important knowledge of local social conditions and a nuanced understanding of the resource system that is frequently lacking in projects managed by outsiders.

A new wave of research into community-based environmental management has followed, both experimenting with new structures and recognizing that rural and Indigenous communities have been successfully practicing traditional forms of common resource management around the world for thousands of years [11, 15, 48, 75, 76]. Indigenous lands are often more sustainably managed than those managed by public agencies [38, 48], using local and traditional knowledge, worldviews, and practices. To achieve the best long-term environmental and social outcomes, it is imperative to empower rural and Indigenous communities to manage their local resource systems.

Community-based methods have limitations and need to be considered in the context of global political and economic forces. For hundreds of years, rural and Indigenous people have gradually lost control of their lands and waters to external actors [63, 71]. Global increases in migration disrupt the relationships between communities and their resources, risking the loss of traditional management systems and posing new challenges [52]. Ostrom's analysis described functional requirements for community-based institutions, including prevailing norms of trust, rights and capacity to self-organize, and mutual monitoring among resource users [57].

Contemporary technologists and computer scientists have begun to grapple with environmental issues using a variety of approaches [24, 30, 59], but engagement with community-based resource management has been sparse. Historical barriers have included the large up-front investments needed to deploy technologies in low-income and remote locations, underdeveloped participatory research methods, and institutional factors that inhibit the uptake of social science ideas into environmental and conservation discourses. However, with the explosive adoption of mobile phones and computing across the developing world [39] and the continued intensification of global natural resource crises, the time is ripe for research into community-oriented conservation technologies.

Local participants in conservation projects often have expertise in traditional management systems, local ecology, and local social conditions. Therefore, it is critically important for locals to have decision-making power in community-based technology projects. There is often a major power imbalance between affluent technologists and the rural communities managing a natural resource, and technologists must be extremely careful not to overpower local voices. Here, community-oriented conservation technologists have opportunities to benefit from hard-earned lessons in other fields, such as public health and *ICT4D*.

In this article we use these lessons and Ostrom's principles of common-pooled resource management to suggest potential technology research directions for community-based resource management institutions. Potential applications include:

- Tools for resource users to mutually monitor each others' usage, and for monitoring the resource state
- Tools to define resource system boundaries and communicate them to outsiders
- Tools for surveying and building data pipelines that characterize the resource system
- Processes for maintaining open channels of communication among all stakeholders
- Processes for building *social capacity*, a group's ability to organize and act positively for mutual benefit

2 RELATED WORK IN ENVIRONMENTAL STUDIES

To motivate the development of community-oriented conservation technologies, this section provides examples of community-based institutions and outlines relevant ideas from environmental studies.

In response to historical shortcomings in addressing the worsening natural resource crises, recent counter-narratives have arisen in environmental studies that incorporate social sciences. Unlike earlier purely biological and Malthusian narratives, the study of *political ecology* emphasizes political and economic forces in natural systems [63]. The related study of *environmental justice* emerged from urban activists fighting for recognition of the fact that low-income communities and racial minorities have much greater exposure to pollutants [43, 68]. Both movements recognize that conservation programs create winners and losers instead of being purely benign.

Conservation efforts are often externally imposed upon marginalized people and people of "developing countries" by first-world environmentalists. There is a long history of forced removal of native populations from their ancestral lands in the name of conservation [63], their presence seen as threats to the "pristine", "natural" environments. For example, conservation refugees were created by the violent expulsion of the Miwok people from Yellowstone National Park in the late 1800's, and the recent expulsion of the San people from the Kalahari [31, 48, 71]. A body of institutional ethnography on many conservation project sites has documented resentments and tensions between external conservationists and local people [75]. Locals and outsiders frequently do not have the same goals, locals often must work very hard and do not feel that they adequately benefit; traditional environmental knowledge is lost; and locals are often made promises of "development" from the conservation projects that they do not feel they receive [75].

Conservation initiatives driven by local communities frequently have advantages over externally imposed ones: locals tend to have a more nuanced understanding of the system's characteristics and history, and the surrounding economic and social systems. Local resource users can devise systems that better match local conditions and often resent rules imposed from afar [57].

Apart from having local knowledge, rural and Indigenous communities around the world can bring important cultural values and perspectives to conservation projects [48]. Government and NGO decisionmakers can be located far from the lands in question, and locals must live with the consequences of their management decisions while outside agents do not. As noted by Gordon et. al., *"If Tribes accept prescribed fire to improve the condition of their forests, they get to breathe the smoke"* [38]. Governments are often criticized for over-prioritizing resource extraction for short-term economic gains, while many Indigenous cultures take a longer-term view; this is most famously exemplified by the *seventh generation principle*, by which many Tribes consider the impact of their decisions on their distant descendents, whom they will never live to meet [48]. Some rural and Tribal communities practice spiritualities that place higher value on a harmonious relationship with the natural environment [48].

The changing world and acceleration of globalization present complications. Migration is changing the relationships between people and their environments, disrupting traditional knowledge and management systems, and posing new challenges [52]. External agencies can support community organization in a number of ways, by providing information or resources, advocating for communities' rights, helping them to navigate political and legal systems, or encouraging them to self-organize [25].

2.1 Examples of Community-Based Conservation Institutions

A wide variety of successful common-pooled resource governance systems exist around the world; many are hundreds of years old, while others have been instituted in the last decade. Here, we provide some examples of joint resource management to contextualize the discussion.

Native American Tribes are regional leaders in environmental management in the Salish Sea area of Washington State and throughout the USA. They operate independently of state and federal governments, both managing their own land and litigating with regional governments to drive conservation agendas [23]. The Tribes use a variety of governance structures, frequently with a consensus model [48], and form inter-Tribal organizations—like the Northwest Indian Fisheries Commission [3]—to coordinate broader efforts. Tribes around the Salish Sea have leveraged treaty rights to spearhead a massive salmon recovery effort which has produced a range of secondary environmental outcomes, like habitat restoration for other species [64]. Tribal forest management, by many measures, is frequently more successful than practices by government agencies on public lands [38, 48]. Increasingly, Washington-area tribes are being awarded government contracts for conservation projects because of their proven successful track record.

As another example, in India's joint forest management model, committees are formed within villages that act as liaisons between local communities and government forestry services. In 2010, India had 106,482 registered Joint Forest Management Committees [15]. Collective forest management is practiced in dozens of countries, with heavy support from NGOs and the UN's Food and Agriculture Organization [34].

Finally, the six-country *Coral Triangle Initiative on Coral Reefs, Fisheries, and Food Security* is a large and well-studied conservation initiative. It provides a case study of small, community-based organizations that receive support from larger coordinating institutions. Over 16,000 no-take marine protected areas have been established in the Philippines under the initiative, mostly supported by fishing communities who see increased fishery productivity from their management efforts. Management decisions are made at a community level. Governments, NGO's, and development organizations like USAID play a coordinating role [77] to address overfishing and destructive fishing, establish protected areas, and manage watershed pollution and coastal development. A major challenge for the initiative has been the building governance capacity: fisheries are exploited by outsiders, and a body of NGO's and international organizations has urged the development of legal institutions to increase the authority of local communities and of leadership and institutions [76]. Law enforcement in many locations lacks the capacity to protect fisheries, and volunteer-run citizen groups have emerged to patrol them, like *POKMASWAS* and *Guardians of the Sea*. The initiative runs many outreach and education efforts, like the *Talking SEA Newsletter* [10] (translated into local languages), video production, village workshops, and seminars for government workers.

3 RELATED WORK IN COMPUTER SCIENCE

Little computer science research has addressed community resource management directly, but has engaged with many adjacent areas that can serve as a foundation.

3.1 Conservation Technologies

Conservation technology is a rapidly growing field that currently focuses on sensing and monitoring. Progress in this area has markedly accelerated over the past decade, with a wave of increasingly available satellite imagery, cheapening of sensors, and improvements in artificial intelligence. Recent prominent applications include measuring biodiversity to evaluate conservation projects and identify biodiversity hotspots for targeting; and assisting in enforcement efforts against illegal logging [50], poaching [17], fishing [5], and wildlife trade. The latest wave has leveraged artificial intelligence analysis over data from satellites [5], camera traps, drones [17], audio recorders [21], and citizen science.

Because of the newness of these technologies, a major challenge is finding ways to embed conservation technologies into resource management systems. Current work takes a birds-eye-view perspective, gathering and analyzing data to inform biology research, policy, and law enforcement efforts. Most efforts have been conducted by large institutions with the technical capacity to handle large datasets and implement policies.

The expense and required expertise of these initiatives creates difficulties for technology adoption by small groups. However, some groups have overcome these difficulties by tapping into the newly emerging "hacking" culture in conservation technology, producing devices like low-cost audio recorders that can be assembled for under $50 USD [44]. Other emerging examples and models of designing and deploying small-scale conservation technology include: (1) a project to reduce the workload of foresters by augmenting their on-the-ground forest inventory data with aerial remotely-sensed data [1], and (2) medium-sized organizations like Wildbook, which mediates between small conservation projects and larger technology providers [6]. Further work is needed to understand how to make recent conservation technologies relevant to small-scale and community-based management institutions.

3.2 HCI for Sustainability

The *Human-Computer Interaction for Sustainability* (HCI4S) field emerged in the 00's to investigate technology's role in mediating peoples' interactions with the natural environment. HCI4S has several approaches through which individuals can interact with companies or government agencies to manage resources, but there is a scarcity of community-oriented work. Approaches include systems for petitioning governments [26], studies of social media activism around environmental topics [81], or collaboration software for reducing energy usage within a firm [54]. Other initiatives seek to help individuals reduce their resource consumption for the benefit of others, appealing to the users' moral senses, but acting on an individual scale instead of negotiating tradeoffs among appropriators.

These approaches have limited applicability to rural and developing contexts because most HCI4S research is situated within cities and developed economies. In contrast to rural venues and much of the developing world, HCI4S contexts feature courts that are powerful, businesses that are well-established and have a large degree of influence on the human ecosystem, and resources that are abundant. HCI4S artifacts do not typically ask users to make substantial sacrifices; rather, they prompt them to assume minor inconveniences such as remembering to turn off an appliance or turn down the heat in their homes [30].

3.3 Computing for "Development"

The field of Information and Communication Technology for Development (ICT4D) typically studies technology use in low-income and developing contexts.

Many HCI4S frameworks are not applicable in developing-world contexts. People in rural, low-income circumstances tend to have much more direct relationships with their natural environments [41], needing to eke out a living from their immediate surroundings—e.g. about 60% of people in India are smallholder farmers—instead of interacting with the environment through the long, detached supply chains of developed economies. Courts and law enforcement are less strong, and corruption tends to be more pervasive. Resources can be much more scarce for people experiencing poverty; restrictions or disruptions in access to important resources like water or firewood can cause severe hardship.

Conservation technology has the potential to benefit from the expensive lessons learned through ICT4D projects in sectors like health and education. At the onset of ICT4D research, there was a broad, naive excitement; technologists pursued a variety of overly optimistic ideas with a supply-driven tech push. However, early ICT4D health projects tended overwhelmingly to be short-lived, disconnected, expensive pilots with disappointing results [36]. ICT4D researchers and practitioners are frequently criticized for "parachuting in" new technologies from afar with little consideration of local circumstances; and for "techno utopianism:" over-reliance on technologies to address problems with social and institutional causes [66]. Uganda even issued a moratorium on ICT4D health pilots in 2012, frustrated with the lack of coordination among donors and government health agencies [51].

The resulting blowback led to a discussion about the steps required to have sustained impact. Donors pushed for guidelines, which led to the widely adopted Principles for Digital Development [4], and academics produced a discourse on ICT4D ethics [27]. There has been a subsequent maturity in some projects, with longer engagements and tighter ties with governments.

As the field of ICT4D has matured, it has developed lenses for considering cultural, social, community, and institutional factors in technology interventions [19, 28, 33, 66]. For example, the influential "amplifier principle" posits that new technologies tend to reinforce existing institutional forces instead of "leveling the playing field" [66]. ICT4D research has produced an extensive discourse on research methods for cases where a substantial power imbalance exists between researchers and participants [12, 29, 70].

Technologies are embedded in complex social, cultural, and institutional systems that determine whether and how people make use of them. The conservation technology domain can avoid repeating mistakes by building on lessons and frameworks from fields like ICT4D, hopefully short-circuiting the long slog of failed interventions.

4 STRUCTURAL CHALLENGES

Socioeconomic, cultural, funding, and institutional factors hamper work between computer scientists and rural conservation institutions. Such challenges help to explain why these relationships have not matured to date. Some of the following problems may need to be addressed by institutional changes before rural voices can be more effectively brought into the discourse on conservation technologies.

The field of conservation technology has a dominant focus on ecology research and enforcement applications. Conservation technology has only a small number of significant funding organizations, and their historical partnerships have steered the direction of the field. Large, well-established conservation NGO's have the social networks to undertake technology projects, while smaller organizations often lack connections. (The focuses of conservation technology also reflect broader trends in environmental management circles, where the discourse is dominated by natural scientists and social scientists have less influence [45].)

Rural community-based institutions often lack the capacity for technical projects, requiring substantial up-front investment to deploy technologies and train users. Rural, low-income and developing world communities often lack computing devices, network connectivity, reliable electricity, formal education, and technical literacy. The technology gap itself is a social injustice. Transfer of technology and computer science education is necessary to support community-based initiatives, which can be a slow and expensive process. The technology gap is narrowing, though, with the rapid uptake of mobile and computing technologies in the developing world [39].

ICT4D research has also established that outsiders working in developing regions often overestimate technology literacy barriers. When they are motivated, novice technology users are surprisingly capable of overcoming obstacles like connectivity, language, cost, and interface complexity [56, 69]. The widespread perception that technologies require simplification for users in the developing world can sometimes be unnecessary and even counterproductive: technology uptake is slow in many cases because outsiders misjudge participants' motivations [56].

Voices of rural participants are not adequately reflected in the environmental research discourse that influences funding and policy; decisions tend to be made by outsiders. For example, citizen science, a popular method for environmental researchers, aims to crowdsource knowledge from non-scientists. However, a 2017 survey of citizen science projects found that participants' roles are largely superficial [18]: they usually do not play any role in project design or data analysis, but merely serve as data-collection instruments for researchers. Computer scientists have more credibility in the eyes of funding organizations and have easier access to funding, giving them considerable power over rural collaborators. Environmental technologists and funding institutions are better set up to work with larger, better-funded organizations who have already proven capable of managing computer systems and handling large datasets.

The need for scalability also causes a tendancy for centralization of conservation technology projects. The diversity among small communities requires diversity in resource management institutions, and technologists commonly perceive a tension in the particularity and customization of community-based solutions [65]. A key advantage of ICT's is their ability to be cheaply replicated and scaled, so technologists are drawn towards generalizable, global-scale problems and broad viewpoints. Lowering the cost of customizing technologies for individual communities remains an important technical challenge.

Technological interventions can do little to address many of the massive global economic structures that impact the ability of communities to manage their own resources. For example, low-income countries commonly cede fishing rights to the industrialized fleets of wealthier nations in exchange for development aid [8, 9]. Globalization is breaking down local boundaries and reducing communities' autonomy over their local lands and waters. Many populations are faced with exploitation of their local resources by outsiders over which they have no control, and stronger legal institutions are needed help local communities maintain control.

5 OSTROM'S THEORY OF COLLECTIVE RESOURCE MANAGEMENT

Here we briefly summarize the work of Elinor Ostrom in *Governing the Commons* [57], which we subsequently use as a framework to suggest computer science applications for community-based resource management. Ostrom's work amassed and analyzed a large body of case studies on successful community-based institutions for managing common pooled resources, which were organized without coercion by a state or firm. Cases ranged from tens to hundreds of years old, including Swiss pastures, Japanese forests, Filipino irrigation systems, and Californian groundwater basins.

Using economic lenses to analyze the systems of incentives in these institutions, Ostrom developed a body of economic theory that demonstrates how collective action can emerge even in a group of fundamentally self-interested resource users, (referred to as *appropriators*), allowing them to escape the tragedy of the commons. From examining cases of success and failure, Ostrom identified three key needs for collective action on common pooled resources:

(1) **Supply of new institutions**: When institutions are first formed or change, appropriators need to agree on a set of rules to adopt. There may be motivation to adopt rules to reach an equilibrium that is better for everyone, but new rules usually do not benefit all participants equally, and participants will each prefer rules that give them an advantage.
(2) **Establishing credible commitments**: Once rules are established, participants must continuously choose to follow them; the resource system will only be sustained if nearly everyone complies. The temptations to break rules are often great—Ostrom notes *"breaking the rules may save an entire crop from drought."* To remain committed, participants need ongoing reassurance that everybody else is following the rules; nobody wants to be a "sucker."
(3) **Mutual monitoring**: Establishing commitments requires mutual monitoring, and someone must put forth the necessary effort for monitoring work. Additionally, there may be social costs for ostracizing a rule-breaker: for each individual member, it may be better to remain passive towards a rule-breaker even when penalizing them would benefit the whole group.

From her case studies, Ostrom developed design principles for successful medium-sized community-based management institutions, listed in Table 1. In the next section, we use Ostrom's principles to outline potential technology applications.

6 TECHNOLOGY OPPORTUNITIES

Based on Ostrom's principals for common-pool resource management, we posit ideas on computing technology applications for community-based environmental institutions. We show some existing examples of how technologists can interact with community-based institutions, and suggests ideas for some new directions.

Notably, this application of Ostrom's principals is itself an imposition of western academic ideas onto people of other cultures, who have different ways of conceptualizing their resource management practices—it is important for local resource managers to have decision-making power in technology projects. Ostrom's frameworks are useful for reasoning about potential technology projects though, because they provide a bridge between many traditional practices and western academic thinking.

6.1 Monitoring

6.1.1 Monitoring of outsiders. A major focus of recent conservation technology work has focused on monitoring for enforcement against illegal logging, poaching, and fishing. Monitoring technologies have largely been designed in partnership with powerful institutions such as national governments and militaries, geared toward external enforcement systems instead of enforcement within a community. Threats to natural resources occur in an increasingly global economy, where community outsiders poach and extract resources that are shipped worldwide. The nature of the modern illegal resource trade violates Ostrom's first principle for community-managed resources; local communities do not have control over their resources' boundaries in these situations. Because poachers are often armed and dangerous, anti-poaching institutions often have military characteristics: many wildlife reserves in developing countries are led by former American and European military personnel. Governments tend to manage them centrally instead of taking a community approach, because they are hesitant to encourage armed conflict between civilian groups.

A range of technologies has been deployed against illegal resource harvesting. Some protected areas are patrolled by drones, detecting poachers at night with infrared heat cameras, and deforestation is monitored with drones and satellite imagery. Several mobile-phone software platforms have been specially designed for rangers with limited technology literacy to manage information [2, 73]. Audio sensors are deployed to detect gunshots [44].

Table 1: Elinor Ostrom's design principles for successful common-pool resource management institutions (adapted from *Governing the Commons* [57])

1	**Clearly defined boundaries** Individuals or households with rights to withdraw from the resource must be clearly defined, as must the boundaries of the resource. Stakeholders need a common understanding of the resource system, agreeing on inflows and outflows.
2	**Congruence between rules and local conditions** Resource appropriation rules (restricting time, place, technology, and/or quantity) and provision rules (requiring labor, material, or money) are related to local conditions.
3	**Collective-choice arrangements** Most individuals affected by the operational rules can participate in modifying them.
4	**Monitoring** Monitors, who actively audit resource conditions and appropriator behavior, are accountable to appropriators or are the appropriators.
5	**Graduated sanctions** Occasionally when under stress, appropriators must bend the rules. They are well-aware and sympathetic to each others' circumstances, and thus minor or neccesary infractions are punished lightly. Punishments are more severe when a member repeatedly disregards the rules or poses a more serious threat to the resource. The ability of community organizations to be lenient based on local understanding of the situation and mutual dependence is a strength.
6	**Conflict-resolution mechanisms** Appropriators and their officials have rapid access to low-cost local arenas to resolve conflicts between appropriators and officials.
7	**Minimal recognition of rights to organize** The rights of appropriators to devise their own institutions are not challenged by external governmental authorities.
8	**Nested enterprises** Appropriation, provision, monitoring, enforcement, conflict resolution, and governance activities are organized in multiple layers of nested enterprises.

There is potential for ICT's to help community resource institutions protect resources from outside threats, and to engage with external institutions in collaborative enforcement [32]. For example, anti-corruption e-government platforms like WildLeaks facilitate whistle-blowing for embezzlement of protected resources [7]. Participatory mapping applications have enlisted community volunteers to report illegal logging roads to enforcement agencies [32], and to report on poacher locations or bad behavior of rangers [74].

Technologies can also potentially improve the safety of volunteer-run enforcement groups like *POKMASWAS*. Some conservation projects like Vulcan's *Skylight* provide information on "dark" fishing vessels to enforcement agencies [5]; it is likely that some enforcement technology projects are already working with community-based organizations but do not disclose the partnerships for tactical reasons.

6.1.2 Community monitoring. Community-based organizations have additional monitoring needs: Ostrom posited that community members must have mechanisms for monitoring each others' resource use. Good monitoring and enforcement ensures that rules are followed and helps maintain appropriator commitment by increasing their confidence that they are not being disadvantaged. Since monitoring is costly and time-consuming, somebody must be incentivized to do it. Successful mechanisms involve monitors receiving some portion of the fines from a caught infraction, monitors receiving some information benefit, or actors most concerned about one another other cheating being in direct contact.

Technologies for within-community monitoring are underexplored. Deployment of sensors and data management systems like Open Data Kit [20] have potential to lower the cost of monitoring, and communicate about the monitoring.

6.2 Boundary and Resource Understanding

For community-based management to succeed, Ostrom postulated that there must be clear boundaries of the resource itself and a clearly defined group of stakeholders allowed to use the resource. The resource cannot be publicly open to everyone. Without clear boundaries it is impossible to enforce any limits on resource extraction or know which parties to involve in governance processes.

Stakeholders need a common, clear image of how the resource system works in order to reason about management decisions. Ostrum illustrated this problem using the example of California's groundwater negotiations in the 1970's [57]. Stakeholders disagreed about the geological structures of the water basins and the quantities of water inflow and outflow. Only after a study was commissioned by the US Geological Survey and results were published—clearly outlining the boundaries of the water basin and clarifying the amounts of inflow and outflow—could negotiations proceed.

6.2.1 Participatory Mapping. Participatory mapping is one example of how technology can help to define resource boundaries: a genre of projects has helped community members document traditional lands and resources. These approaches can help to shape within-community understanding of the resource system and its current uses, as well as to communicate the resource boundaries to outsiders [53]. Many global Indigenous communities are faced with an unrelenting threat of intrusion upon their lands and resource theft, such as illegal mining and logging. Previous case studies have shown the usefulness of participatory mapping for asserting land rights—use of technology gives the claims of Indigenous people more credibility in the eyes of government decision-makers [80].

Mapping played an important role in the origins of environmental justice: activists in the 1980's used maps to show that urban low-income and racial minority communities were disproportionately exposed to greater levels of pollution in the USA [68]. A large community of academics and practitioners use maps for environmental justice purposes [40, 43], and have produced a substantial relevant literature on the challenges of achieving deeper levels of community engagement and meaningful community empowerment [18, 65]. The participatory mapping literature has continually grappled with problems like the top-down intercession implied by "participation", and the sometimes-uneasy collaborations between academics and government agencies with activists whose motivations are more oppositional and confrontational [65].

6.2.2 Surveying and Information Gathering. Studies required to understand the nature of a resource system can be prohibitively complex and expensive for community-based institutions. Forest inventory is one example. In many forestry practices, timbre and other resources require regular and precise measurement to determine the amount that can be harvested without damaging the forest's ability to regenerate. Forest inventory can be prohibitively time intensive and complicated for small organizations. A study of community forestry organizations in Cameroon found that most were unable to complete the forest surveys required by the government [34].

Computing technologies can simplify resource study tasks for community management institutions. For forest inventory, there has been momentum in research towards computer vision tools to simplify the process, but these tools are still targeted towards highly trained professional foresters, and scant work addresses making them accessible for remote and low-income contexts. Examples of such computer vision tools include automatic species identification from photos [14], assessments of tree volumes from collections of images [55], measurements of light penetration and vegetation density, and the integration of satellite imagery to reduce surveyor workload [1]. One interesting case from fishery management is the provision of fish-finding technology to subsistence fishing communities, which can reduce the reliance on destructive methods like dynamite fishing [35].

There is also potential for data-collection technologies to help local communities gain decision-making power, by building trust with larger institutions. For example, the USA has been persuaded to give more management rights to Tribal communities because many Tribes rigorously and empirically demonstrated the effectiveness of their management strategies [38].

6.2.3 Information Dissemination. Computing technologies can play a role in sharing information among stakeholders through a number of channels, like phone-based forums, videos, radio and visualizations. Community radio has been utilized for many environmental initiatives in low-income regions; for example, social campaigns by Gram Vaani in rural India asked people to call a hotline and voice concerns about water quality issues, which were broadcast over the radio [67]. Landscape visualization technologies with Indigenous communities have proven helpful for including less-technical stakeholders in decision-making processes [47].

6.3 Social Capital and Capacity Building

"Social capital" is a theme which runs through many of Ostrom's principles; referring to the relationships among people who live together in a particular society that allow them to organize and work together effectively. To organize management institutions for a natural resource, members need to feel like they can discuss their problems and be optimistic that they can work together to address them. A resource-management community needs a sense of identity and shared values; members must trust each other and form productive working relationships. There may be a danger of eroding social capital by substituting face-to-face interactions with technology. The concept social capital could be a useful technology design lens for trying to strengthen conservation institutions, and addressing possible harms created by technology's proliferation.

Ostrom illustrated the concept of social capital with the example of a Sri Lankan irrigation system that had fallen into disrepair and disuse during a period of fighting and political turmoil. Many users of the irrigation system were new migrants to the area and did not trust each other. Students from Cornell's development economics program were sent to organize farmers into small groups with neighbors, who met regularly to discuss concerns. After several months the groups could form a larger organization to manage the irrigation system. The marginal cost of forming the large organization was much lower once the smaller organizations were already in place with behaviors already established [57].

6.3.1 Social Media Activism. Researchers have examined the use of online social networks and social media for environmental purposes. Social media is used to agitate against governments for environmental causes in many Indigenous and developing-world contexts [72, 79, 81], and is also commonly used to coordinate within conservation organizations in more-connected countries like the Philippines [62]. There is potential for technologists to investigate technology-enabled social networks in areas with less connectivity, perhaps drawing from related ICT4D projects using voice-based technologies [60, 67].

6.3.2 Documenting Indigenous Knowledge. A growing body of work focuses on digitizing Indigenous environmental knowledge, to communicate with outsiders and pass down traditions via young peoples' enthusiasm for technology. Efforts have focused on multimedia techniques for recording stories [13] and highlighted the inadequacies of conventional information technology for encoding important factors in many Indigenous knowledge cultures, such as narrative elements; structural variations; and spatial, temporal, and interpersonal relations [78]. Projects have explored ideas to incorporate multimedia into traditional dialogue and decision-making practices [49], and (controversially) to include oral citations on Wikipedia [37].

7 RELATIONSHIPS BETWEEN COMMUNITY RESOURCE MANAGEMENT AND TECHNOLOGISTS

It is vital for resource-management communities to take the lead in interactions with technology researchers. However, there are many structural obstacles in these relationships. Locally led initiatives have better conservation outcomes than externally imposed initiatives in many circumstances, but because technologists tend to have greater socioeconomic power, there is a serious danger of local voices being crowded out in the design and implementation processes. It is crucially important to the uphold respect of participating communities and to avoid impinging on their autonomy.

The bulk of conservation technology initiatives take a supply-driven, top-down approach. Technology developers and deployment architects usually live in cities and make decisions from afar, operating from a high-level, global viewpoint. A key research challenge is to develop collaboration models with communities who live closer to resource systems, giving them more agency in both technology design and deployment.

Communities are made up of many different actors, groups, and institutions who have differing motivations and ideas about natural resource management [11]. In an increasingly heterogeneous world, patterns of migration and economic development have many groups of people managing and depending on the same resources. There are often apparent benefits to empowering small local groups, but technologists—deliberately or not—are faced with decisions about *which* locals they work to empower. Adopting technologies in resource management processes can shift power to younger, wealthier, and more tech-savvy members of the community [65]. Important actors might not have the time to participate.

A variety of participatory collaboration models have been explored in computing and design research [16], but models in which participants truly *lead* research directions are still underdeveloped, especially in cases where there is a large gap in computing literacy between researchers and participants [61]. Technology development and adoption has considerable time cost for participants, and partners from rural communities should receive compensation.

Conservation technology can potentially benefit from the growing movement within ICTD research that emphasizes local knowledge and social capacity building [46], incorporating ideas from the field of knowledge management. The success of global conservation efforts heavily depends on local knowledge, and this demands greater acknowledgement of other knowledge cultures within circles of power.

Marginalized communities must have agency to determine for themselves how much involvement they have with technologists. Communities who manage common resources are heterogeneous, and have varying degrees of desire to interact with external researchers and technologies. Tribes in the Salish Sea area, for example, employ some of the best lawyers and biologists in the region [3]. Some other Indigenous groups, though, are reluctant to engage with westernized institutions, instead prioritizing the preservation of their longstanding traditions and cultures [48]. Global conservation efforts would benefit from better communication channels to enable community resource management institutions to reach out to technologists with their own needs and ideas, instead of relying on supply-side pushes from technologists.

Considering Ostrom's recognition that resource management communities need the power to change their rules, the inflexibility of computing technologies presents a problem. Software and hardware can be prohibitively difficult for non-technical users to modify. Technologists ought to strive for flexible solutions that can be modified by users when local conditions change, and invest in computer science education in communities to build technical capacity.

Despite the considerable costs and time needed, technology and skill transfer to community management institutions is important for global conservation efforts—it is imperative for conservation technology groups to begin the long process of relationship building.

8 CONCLUSION

There are ample opportunities for collaboration between technologists and community-based conservation institutions, and previous academic work on common-pool resource management can provide suggestions for initial research directions. Complex structural factors present challenges in these potential relationships, though, requiring institutional adjustments from technologists and a commitment to more participant-driven research methods. Conservation technologies can benefit from lessons and frameworks from other fields related to global development, like ICT4D, to avoid repeating their mistakes.

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