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Sustaining Workers Who Sustain the World: Assets-Based Design for Conservation Technologies in Madagascar

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Local workers and their knowledge are essential for sustainable and effective conservation efforts. However, many technology-assisted conservation programs are guided by global benchmarks (e.g., forest cover) and industry metrics (e.g., cost per acre), which often devalue local knowledge and fail to consider the economic and conservation goals of local workers. Assets-based design is well-suited to center workers and their strengths, yet it may fail to fully address the complexities of long-term conservation programs by not explicitly emphasizing workers' goals or bolstering their assets. We extend recent approaches in assets-based design literature that address these limitations through our case studies of reforestation, biodiversity monitoring, and carbon sequestration programs in three protected areas in Madagascar. We leverage a mixed-methods approach of direct reactive observations, unstructured interviews, and an informal design workshop, revealing emergent themes surrounding economic sustainability and the value of local ecological knowledge in conservation. Finally, we explore examples, tensions, and design considerations for worker-centered conservation technology to: (1) prioritize local knowledge, (2) foster love of nature, (3) center economic goals, and (4) embrace local autonomy. This work advances the dialogue on assets-based design, promoting the co-creation of equitable and sustainable conservation technologies with workers in Global South settings by centering local economic priorities and enhancing workers' strengths.

CCS Concepts: • **Human-centered computing** → **Empirical studies in HCI**; *HCI theory, concepts and models*; • **Applied computing** → *Environmental sciences*; • **Social and professional topics** → **Sustainability**.

Additional Key Words and Phrases: Assets-based design, conservation technology, sustainable HCI, local ecological knowledge, financial sustainability

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1 Introduction

Natural environments provide "ecosystem services" [137], benefits that enhance the well-being of human and non-human species alike. These benefits include healthy food and water, protection from adverse weather, and partial climate stabilization [26]. Each ecosystem provides a unique array of these services, which are constantly in flux due to natural and anthropogenic effects such as habitat fragmentation, deforestation, the introduction of non-native species, and climate change [111, 137]. Thus, monitoring, preventing, and mitigating ecosystem changes are primary goals of many conservation programs [107, 125, 146]. Local workers are often crucial to conservation programs [142], as is their local ecological knowledge (LEK) [57], the "knowledge about nature, including organisms (animals and plants), ecosystems and ecological interactions, held by local people who interact with and use natural resources" [97]. By supplementing and/or replacing human labor and LEK, digital technologies can play a central role in conservation efforts [107].

Our work builds on the fields of Computer Supported Cooperative Work (CSCW) and Human-Computer Interaction (HCI), which study the design and application of technologies as they relate to people, communities, and cooperative work [65, 120], and the subfield of Sustainable HCI (SHCI)that analyzes, designs, and improved conservation technologies [10, 48]. However, the bulk of prior SHCI research has focused on people working and living in North America and Europe [78, 128], whereas much of the world's biodiversity and the people most vulnerable to the impacts of climate change

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exist in the Global South [35, 43][1]. Although CSCW and HCI researchers have studied the design of technology by, with, and for Global South communities, many of these efforts have been conducted under the lens of development, in which these communities are viewed as places that require improvement [49]. Additionally, SHCI literature has largely neglected the economic component of sustainable technology [124], a necessary aspect for centering local conservation workers. Nearly half of papers in a recent HCI for development literature review focus on mobile phones [28] which are not widespread in many rural communities in the Global South [29, 49, 148, 150] and raise challenges for those with limited literacy [84].

Although researchers already explore SHCI technology in Global South settings, particularly for acoustic sensing [31, 32, 78], an opportunity remains for technology design with local conservation workers. Assets-based design is a participatory approach championed to inform sustainable and just technology design [22]. This approach is well-suited to center workers and their strengths, and recent research has identified opportunities for it to illuminate community goals and support the continued asset growth [145]. We extend these findings to 1) sustain their assets, primarily local knowledge and love of nature and 2) incorporate their economic and autonomy goals.

In this paper, we describe our qualitative methods documenting the technologies and collaborative work processes for conservation efforts in Madagascar. A biodiversity hotspot in the Global South with over 90% of its plants and animals found nowhere else in the world [111], Madagascar is an ideal location for high-impact conservation. We center three case studies– reforestation, biodiversity monitoring, and carbon sequestration– synthesized over multiple conservation projects in Madagascar, centering the experiences of Malagasy workers.

The two first authors conducted qualitative mixed-methods research, including direct reactive observations, unstructured interviews, and an informal design workshop, across three protected areas over four weeks. Using field notes from the trip, the research team identified collaborative work processes, local ecological knowledge, technologies, and data that conservation organizations employed towards their biodiversity monitoring, reforestation, and carbon sequestration goals. To identify emergent themes, the first author and one author who did not participate in the fieldwork analyzed the field notes using reflexive thematic analysis [15, 16].

Synthesis of these three use cases in conversation with CSCW literature reveals emergent themes, tensions, and design considerations. These justify the need to re-center *economic* sustainability and autonomy of local communities in technology design and question assumptions around what technology roles are most beneficial. We stress the often invisible roles that local knowledge and love of nature play in all stages of conservation and offer suggestions for designing technologies that bolster workers' ability to sustain these attributes.

We identify three main contributions from our work:

(1) Documenting the collaborative work processes, local ecological knowledge, technologies, and data involved in three conservation case studies in Madagascar.
(2) Furthering CSCW discussions around themes of sustaining local knowledge, fostering love of nature, centering of economic sustainability, and embracing local autonomy through the lens of conservation work in the Global South.
(3) Presenting design considerations that extend assets-based design principles under broad conceptions of sustainability.

[1]We choose to use the term "Global South" over "third-world" or "developing countries" as it eliminates the hierarchy or negativity that may be associated with these other terms. We considered the term "Majority World" but found it created confusion.

2 Related Work

Our work builds on and contributes to literature from CSCW, HCI, and Information and Communication Technologies for Development (ICTD). We build on work from Sustainable HCI, HCI in the Global South, HCI and Work, HCI and the Intrinsic Value of Nature, and Assets-Based Design. In this section, we provide an overview of pertinent prior works, which we engage with further in the Discussion section.

2.1 Sustainable HCI

With the growing awareness of environmental challenges such as biodiversity loss and climate change, Blevis and other HCI researchers began to explore the design implications of sustainability in 2007 [10]. The movement grew into the Sustainable HCI (SHCI) subfield [34], which has blossomed in recent years with hundreds of relevant papers published since 2010 [48]. Researchers have noted that there is not a consensus around the scope of "sustainability" in SHCI [90], and prior work has almost exclusively focused on environmental sustainability [48, 124]. However, many in the broader research community emphasize definitions of sustainability that extend beyond just the environment [11, 80, 84, 90].

Modern approaches to sustainability focus on the *three pillars of sustainable development* – social, environmental, and economic [84, 124, 128], which originated as early as 1987 [110]. Through the lens of the three pillars, "research that seeks sustainable solutions to protect the environment also strengthens our communities and fosters prosperity" [136], helping to push towards the broader sustainability goals as defined by the United Nations [135]. Some HCI work has noted the importance of the three pillars in designing for environmental sustainability, with Masinde et al. [84] noting that the three pillars are the basis of social and environmental justice, and Blevis stating that sustainability should extend "beyond the environment to include notions from respect for human labor to respect between nations" [11]. However, a recent SHCI literature review found that only 5% of SHCI papers touched on economics as demonstrated in their Venn diagram, shown in Fig. 1 [124]. Another review found that none of the 51 papers reviewed mapped to Sustainable Development Goal 8: "Decent Work and Economic Growth" [48].

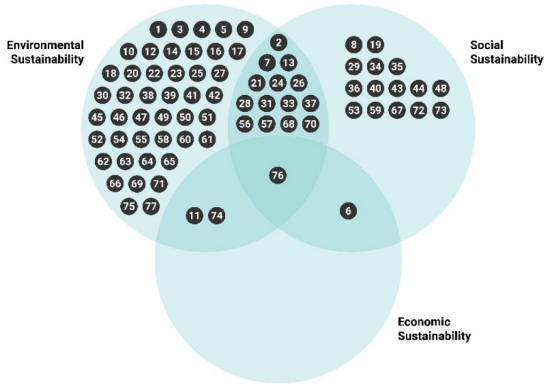


Fig. 1. Venn diagram demonstrating work in the field of Sustainable HCI. Figure from Scuri et al.'s *Hitting the Triple Bottom Line* [124]

A 2010 literature review found 45% of SHCI papers focused on "persuasive technologies" [34], which encourage users to measure and change individual behaviors [34, 89, 90], such as using

less water [4]. Many other SHCI works focus on "citizen science" [14, 113, 127], which encourages non-experts to contribute to environmental research by collecting or annotating data for free [72]. This focus on individual change and volunteers ignores large swaths of conservation that centers systems and is conducted by professionals. SHCI researchers have also noted that the majority of these initiatives almost exclusively focus on technology users in the Global North [78, 128], raising tensions due to its exclusion of those who are most impacted by climate change [35, 119]. SHCI research in Global South settings often targets foreign researchers rather than Global South community members. For example, Dema et al. [31] examined Australian ecologists' acoustic monitoring in Bhutan, noting the reliance on local people to deploy and manage monitoring devices but focusing minimally on designing technology with that community in mind. Recent CSCW initiatives have responded to these shortcomings by highlighting the need to "support climate justice principles and processes in designing technologies and systems" [35]. In particular, such initiatives ask HCI researchers to question how their research and associated institutions work within or against the principles of climate and environmental justice [35].

Our work contributes to this call by highlighting how designers, technologists, and researchers might work within climate justice principles in biodiverse regions in the Global South. Additionally, our work centers the "support work, people, and artifacts" [54] within Global South communities that enable ecological and conservation research. Finally, we center the economic pillar of sustainability due to its importance to Malagasy knowledge-holders and explore its role in future SHCI work.

2.2 HCI in the Global South

CSCW researchers have increasingly focused on the design, use, and adoption of information and communication technologies (ICTs) by Global South populations [29, 54, 55, 69]. Researchers identified unique challenges, such as language barriers and higher rates of illiteracy, which can make technologies designed for Global North settings unusable in many Global South locations [84, 121], including those with a high level of biodiversity [84]. A 2016 Global South HCI literature review found that nearly half the papers focused on basic and feature mobile phones [28], and more recent works have centered websites accessed through smartphone apps [63, 95]. However, high biodiversity areas in the Global South are overwhelmingly rural [91] and thus often have less communication infrastructure than urban centers [49, 148–150]. Understanding ICT use in "regions constrained by poor infrastructure and limited resources" [29] offers insights to CSCW initiatives for more just design practices [29, 49]. We aim to address recommendations by De Castro Leal for designers to better understand heterogeneous technology use by communities "at the periphery" of global capitalism [75].

HCI research has explored the potential harms of digital technology in the Global South [55, 73], revealing that power relations, colonialism, and geopolitical tensions create challenges around equal access to, representation on, and adoption of digital technologies [27, 53, 55, 121]. Additionally, CSCW research has revealed how the introduction of new technologies can introduce and exacerbate modes of oppression [69]. The concept of "Appropriate Technology" promotes labor-intensive and locally autonomous technology to promote sustainability in poor communities [123] but faces criticism around who gets to define "appropriate" [9, 100] and how it has been co-opted to a "more straightforward focus on control" [94]. HCI researchers promote design perspectives such as postcolonial [53] and decolonial computing [2] to study the imposition and subversion of colonial structures of technical systems [27]. Indigenous decolonization scholarship advocates for tenets including respectful relationship building through reciprocity, in which all parties provide benefits to each other [66, 87, 112]. To address challenges around soliciting genuine user feedback across power dynamics, Chidziwisano recommends a combination of design probes and user diaries that

overcome users' politeness [21]. Additionally, the *Aspirations-Based Design* framework centers communities' goals to design well-aligned technology [70, 133]. We draw on these perspectives, acknowledging the importance of "power, authority, participation, and intelligibility" [27] in conservation technology design in the Global South.

2.3 Assets-Based Design

CSCW researchers increasingly utilize *assets-based design approaches* to address the challenges in designing and deploying technologies with communities in the Global South [143]. Introduced in 1993 by Kretzmann and McKnight, assets-based design began as a framework to "rebuilding troubled communities" [88] by centering a community's "strengths and capacities" [145] to promote sustained positive impact [22]. This contrasts a deficits-based view that can cast the community in an incompetent light [49, 50] and can lead to negative outcomes even when the "right" steps are followed [101]. It has gained traction in political and economic development circles, which have advanced frameworks around sustainable community development based on social capital [85] and grassroots movements [40]. Notably, an assets-based approach "does not imply ignoring problems or needs" but rather serves as a "rallying point for bringing citizens together" [129].

Despite the growing use of assets-based design approaches, a number of questions remain unanswered: 1) which assets should be leveraged in technology co-design [143]? 2) how can the process also illuminate a community's goals [145]? and, from a 2020 CSCW assets-based design workshop 3) how to sustain the impact of design "in the face of intersecting axes of oppression" [144]? We engage with these questions by considering the local employment and autonomy goals within an assets-based framework and extend the goals of technology design to sustain the assets that socio-technical systems rely upon.

2.4 CSCW and Work

CSCW, with its emphasis on work, was established nearly 40 years ago [13]. Although the concept of work has dramatically changed in that time, it remains necessary to understand how technology use can support cooperative processes in various settings [120]. Specifically, early CSCW research revealed the distinction between visible and invisible work [131] and remains relevant today, especially as the Internet and ubiquitous technologies make it easy to work on collaborative processes without physically meeting. More recent work in Global South settings shows that cooperative work processes are poorly understood and often highly contextual [29] and highlight the importance of mapping worker workflows to understand motivations [126]. A 2023 CSCW workshop on labor also encouraged examination of who benefits from labor research and how to make technology accountable to its consequences [132], which we aim to address in the context of conservation workers and technology.

Following questions around the definition of work [120], we promote an expanded view of work in this paper. Specifically, we consider the work and value of the unique *local ecological knowledge* (LEK) of those who live in and near protected areas [12]. Notably, LEK, which is also referred to as "Traditional Ecological Knowledge" or "Indigenous Ecological Knowledge" [118], plays a significant role in many biodiverse Global South settings [78, 84], including in Madagascar [41, 83, 151]. Knowledge-holders accumulate LEK socially and through firsthand experiences over their lifetime [5]. Because LEK is both threatened and essential to the preservation of biodiversity [84], it is imperative that the CSCW community builds on existing efforts aiming to allow communities to preserve and share their LEK [32, 46]. We add to CSCW literature by focusing on employing local community members in conservation efforts in the Global South and showcasing LEK as a core component of work.

2.5 HCI and the Intrinsic Value of Nature

Conservation programs have long focused on promoting the intrinsic value of nature, including for endangered species [18], trees [6], and green spaces [60]. The HCI community's design considerations for non-human animals [81] and plants [39] suggests a recognition of these beings' inherent value. Further, human engagement with non-human animals has gained attention, with recent work noting the challenges of human-centric designs that avoid noticing and identifying with other beings and species [38]. Similarly, a nature-walk based design probe found that time spent outdoors can further develop human empathy for nature to promote environmental stewardship [42], which can be extended to conservation-related tasks such as waste management [77, 117]. In our work, we consider how technology can and should instill a sense of the intrinsic value of nature in its users and the broader community, particularly in a Global South setting with high biodiversity.

In summary, our work contributes to a small but growing body of literature that 1) focuses on the design and use of conservation technology by local community workers in rural Global South settings and 2) provides design considerations within the assets-based design framework. We provide three case studies of conservation programs in Madagascar to provide insight into the heterogeneous goals and technology adoption of workers in these spaces. We leverage these case studies to explore technology's role in centering LEK, fostering love of nature, centering economic sustainability, and embracing local autonomy.

3 Study Context

The economic opportunities and overall prosperity of the Malagasy populace is tightly tied to sustainable relationships with the natural world. With a median age of 19 [64] —similar to much of Africa but far younger than the Global North [1]—Madagascar presents an opportunity to develop locally-situated sustainability interventions with emerging tech-native leaders. 60% of the Malagasy population live in rural areas where subsistence farming is common [64] and 80% are "essentially entirely dependent on natural resources" [98]. As of 2023, 19.7% of the Madagascar population were Internet users and 43.8% possessed cellular mobile connections [64], suggesting that relying on "leapfrogging" [92] by implementing cellphone-based interventions may not be feasible. Madagascar is designated by Conservation International as a "biodiversity hotspot" due to its high number of plants found only in Madagascar and its significant loss of "natural vegetation", one of 36 such hotspots globally [52]. The country also identifies as a Like-Minded Megadiverse Country (LMMC), expressing a commitment to promoting biological diversity in coordination with partner countries [96]. Rainforests hold much of this biodiversity and have become fragmented in most regions, which reforestation efforts attempt to address by connecting continuous stretches of forest known as "biodiversity corridors".

Conservation plays a strong economic role in the communities in and around protected areas, and ecotourism is also economically important for more accessible areas. Payment for local guides and permits are required for any visitor, and conservation projects tend to rely heavily on hiring local staff [108]. The higher range of these salaries is around $250 USD per month, or $1.56 per hour [138]. Local communities frequently play a large role in protecting forests through organizations called Vondron'Olona Ifotony (VOIs) or Communautés de Base (Cobas) that periodically monitor the forest for signs of prohibited human behavior. Madagascar has a strong history of community co-design for research and conservation programs [36, 37], and ecological research continues to debunk the colonial myths of resource mismanagement by Malagasy [33, 130]. Local communities structure management efforts through *dina*: "customary law" associated with self-governance and social contracts [67, 114], which underscores the need for conservation initiatives to engage deeply with local communities to ensure sustainable and respectful implementation. Despite widespread local

conservation efforts, only 8.9% of biodiversity publications from 1960 to 2015 were led by Malagasy institutions [140], suggesting an undervaluing and under-utilization of Malagasy knowledge and labor in Madagascar conservation.

4 Methods

In this section, we describe the process of relationship forming with knowledge-holders, research trip overview, steps taken to collect and analyze data, and author contributions and positionality.

4.1 Relationship Forming

Keeping with the practice of acknowledging the "work that occurs before the work" [74], we describe our process for forming relationships. The second author (2A) made initial engagements with prospective partners based on his prior ecological research in Madagascar. 2A introduced the first author (1A) virtually to these contacts via email and video-calls, which led to conversations in which prospective partners expressed interest in co-designing technical systems that could aid on-the-ground conservation. 1A and 2A engaged virtually with seven prospective partners representing four conservation organizations, each with robust relationships with local communities and other conservation organizations. Many prospective partners expressed that firsthand experience working with these organizations prior to design was essential to the co-design process, and thus the first two authors (F2A) organized a trip to Madagascarin which F2A met additional prospective partners and conservation organizations. The observations, interviews, and workshops described in this work should be understood in the context of the co-design of future technology. Although "technology" in Madagascar conservation manifests in non-digital forms, such as Nomena's pulley system to boost cellphone reception that we discuss in section 5.4, we focused the discussion on digital technology.

Although we referred to these individuals as "prospective partners" during the trip, we describe them in this work as "knowledge-holders" to distinguish between the insight they provided and any future projects. When engaging with these knowledge-holders, we utilized an assets-based approach [62, 144], engaging qualitative methods to understand their strengths that a system could leverage, and in this process we learned about their goals and current practices. We clearly communicated with knowledge-holders that their decision to participate in this work would have no bearing on the direction of future projects. In line with calls to value all intellectual labor [86], co-authorship was offered as a way of acknowledging their role in shaping this paper. 16 knowledge-holders representing seven conservation organizations accepted this offer, many of whom 1A and 2A met for the first time in person during the Madagascar trip. These organizations are Madagascar National Parks (MNP), The Dr. Abigail Ross Foundation for Applied Conservation (TDARFAC), Centre ValBio (CVB), Catholic Relief Services (CRS), Ecole Supérieure des Sciences Agronomiques (ESSA), LIFEPLAN, and Mad Dog Initiative (MDI). Knowledge-holders provided demographic information, which also reveals insight about the makeup of those working in conservation in Madagascar. They represent ages ranging from 25 to 76, with 25% identifying as "F" or "woman" and 75% identifying as "male" when responding to an open-ended inquiry. 75% are Malagasy and 25% are foreigners. They hold a variety of titles and roles, including field directors, graduate students, conservation officers, and organization directors.

Fig. 2. Map of Madagascar, labeled with the three featured protected areas and the capital city.

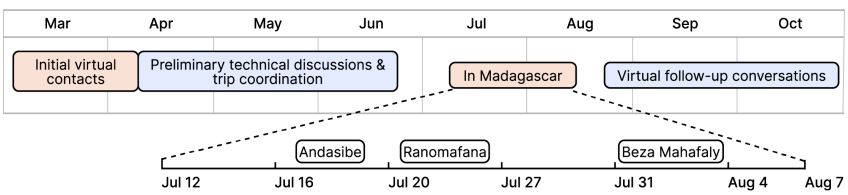


Fig. 3. Timeline of Knowledge-holder Engagement for Madagascar in 2024

4.2 Research Trip Overview

The first two authors (F2A) spent four weeks in Madagascar during July and August of 2024. Conducting a multi-sited ethnographic study [82], they visited communities in and around three protected areas: Andasibe-Mantadia National Park, Ranomafana National Park, and Bezà Mahafaly Special Reserve, as shown in Figs. 2 and 3. Each protected area is an important ecological and ecotourism site administered by Madagascar National Parks (MNP) and has a longstanding presence of research infrastructure and personnel.

4.2.1 Site 1: Andasibe. Andasibe-Mantadia National Park, predominantly composed of primary growth rainforest, has been celebrated as an example of how conservation and tourism can mutually benefit local communities [93]. Knowledge-holders affiliated with the Mad Dog Initiative (MDI), EcoVision, and The Dr. Abigail Ross Foundation for Applied Conservation (TDARFAC) are working closely together to reforest Ecovision's privately owned land to reconnect two flagship parks , as shown in figure 4. At this site, F2A observed acoustic biodiversity monitoring in healthy, degraded, and recently reforested plots, and facilitated a half-day design workshop with two Malagasy project managers.

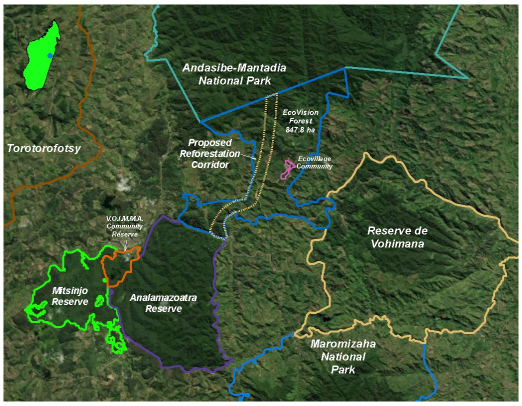


Fig. 4. Map of the reforestation corridor in EcoVision Forest near Andasibe-Mantadia National Park.

4.2.2 Site 2: Ranomfana and Ambodivoangy. Ranomafana National Park, a UNESCO World Heritage site with vast tropical rainforests, houses abundant ecosystem services and biodiversity [61]. F2A visited the nearby town of Ambodivoangy with knowledge-holders from Centre ValBio and Catholic Relief Services who are leading a USAID-funded[2] monitoring and reforestation project with the local community.

4.2.3 Site 3: Bezà. Bezà Mahafaly Special Reserve hosts dry forest and is not nearly as accessible or tourist-visited as the other locations. Here, F2A shadowed and conversed with members of Ecole Supérieure des Sciences Agronomiques (ESSA) Monitoring Team and learned about local ecological monitoring efforts and goals. The Monitoring Team tracks long-term ecological data such as the status of the resident radiated tortoise population and collects weather and community economic activity data around the reserve.

4.3 Data Collection

Prior to their four weeks in Madagascar, F2A coordinated with knowledge-holders to observe and discuss ongoing conservation activities at the three study sites. Drawing on multi-sited ethnographic practices, we employed the approaches of "follow the people" and "follow the thing" [82] to document the processes conservation workers followed and the paths for conservation technologies and data. Based on our desire to minimally disrupt knowledge-holders [25] and to align with recommendations by previous CSCW researchers focused on conservation technology in the Global South [139], we employed a hybrid approach of direct reactive observations and unstructured interviews [8] with knowledge-holders while in the field, offices, and research stations. F2A attempted to engage workers at all levels of the project to "listen and to learn from voices typically absent from the technology design process" [147].

F2A first engaged in direct reactive observations with minimal questions or interruptions, although the mere presence of the researchers likely altered how knowledge-holders went about their work [45]. Following observation, F2A conducted unstructured interviews, modifying the more conventional approach in CSCW work of pairing observation with semi-structured interviews [44, 79] to provide more agency to knowledge-holders in choosing the interview direction and to react to timely topics while in the field. The interviews involved active questions between knowledge-holders and F2A to further document the existing conservation programs and to "future": co-imagine

[2]At the time of writing it is too early to know whether the Trump administration's USAID cuts will impact this program

how processes, technologies, and social structures could change to better achieve conservation goals in the future [56, 68]. F2A prioritized interviews while walking with knowledge-holders in the field, a method noted for its ability to highlight memories, resources, and mental models in participatory design contexts [59] and that promotes sharing of narratives that conflict with those deemed official [109]. A typical process entailed holding preliminary conversations with knowledge-holders about some aspect of their job and organization's goals, field observations as they carried out their duties, field interviews to understand their decision making, and follow-up discussions at the research station to provide more context and answer questions. This process often took place over multiple days, and the observations and interviews often took place iteratively or simultaneously despite F2A's goal of conducting them sequentially.

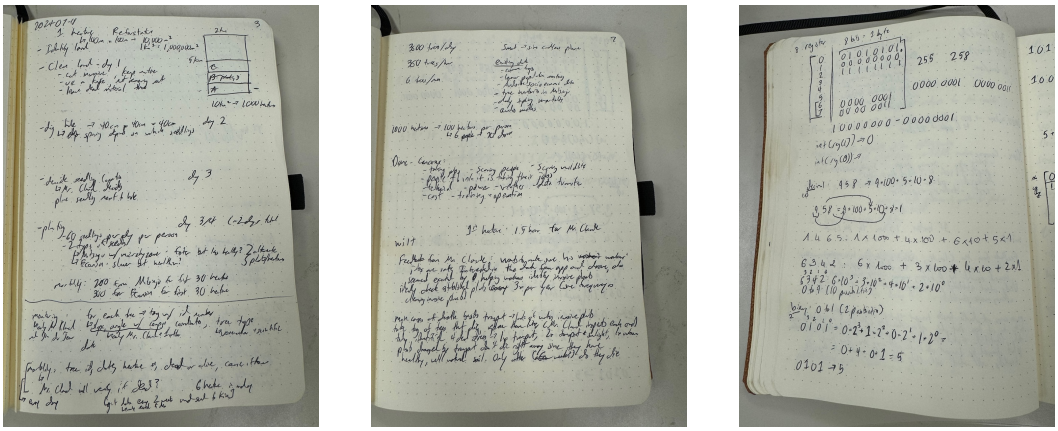
F2A occasionally encountered a challenge in convincing knowledge-holders to go about their typical work as if F2A were not there, with some knowledge-holders explaining that they are accustomed to foreign researchers dictating the agenda. Drawing on practices from the healthcare design space [19], F2A addressed this challenge by facilitating an informal design workshop to more comprehensively uncover knowledge-holders' perspectives. The design workshop constituted a focused period where the authors and knowledge-holders shared individual and organizational goals, coalesced them into common goals for future technology, and brainstormed project ideas that aligned with those goals. After generating this list of ideas, knowledge-holders enumerated potential challenges and opportunities that each would create, and F2A later posed these ideas to other knowledge-holders to garner additional insight. F2A only conducted this workshop at the first site because knowledge-holders at the other two sites seemed more comfortable setting the agenda and sharing their goals and ideas.

F2A took unstructured notes during and after all activities, informally discussing their findings each night and formally reviewing their notes together every few days to note any additional observations. F2A recorded raw notes in physical notebooks (16 pages), a smartphone-based note-taking application (15 pages), and cloud-based text documents (33 pages). Fig. 5 provides examples of these physical notes, demonstrating the documentation of processes, workshop outcomes, and broader exchanges about how digital technology works. At the conclusion of the trip, F2A also distilled observations and reflections from these documents and other experiences on the trip into an additional 51 page note document. F2A did not take audio recordings due to its impracticality in the field and to minimally alter knowledge-holder processes, but they did take over 1,000 pictures to document insights. F2A communicated with knowledge-holders primarily in English and French, but also occasionally in Malagasy with help from a local speaker.

The research team obtained the appropriate permit from Madagascar National Parks and submitted the research protocol with a letter of local support to the Institutional Review Board of the Georgia Institute of Technology, which deemed the research as exempt. All knowledge-holders were informed of the study's goals during the initial conversations and consented to contribute their knowledge and experience.

4.4 Data Analysis

We analyzed the field notes using an inductive, reflexive thematic analysis approach [15, 16, 58], starting from the research question of how best to design sensing technologies with conservation workers. The plethora of field notes, photographs, and F2A reflections offered an opportunity to more deeply understand the intricacies of designing and deploying technologies with conservation workers in Global South settings. An inductive approach was appropriate as conservation technology in Madagascar constitutes "new terrain" [23], and a reflexive approach was instrumental in extracting insights from the field notes co-constructed between 2FA and knowledge-holders [16].



(a) The reforestation process explained by the EcoVision team.

(b) Notes from the informal design workshop at Andasibe.

(c) Notes from a teaching session about binary numbers.

Fig. 5. Three images of 1A's research notebook that demonstrate observations, design workshops, and broader conversations about technology with knowledge-holders.

The last author (LA) reviewed the entirety of field notes, photographs, and reflections, first identifying codes and then themes organically from an objective perspective as someone who did not visit Madagascar or meet the knowledge-holders. LA met with the first author for several hours split over multiple meetings to iteratively discuss and revise the set of codes and themes. LA based initial codes on related observations from across the source material and over time grouped these into broader themes. Throughout the iterative process, the two authors occasionally conferred with the second author to ensure that the themes reflected another perspective from someone on the trip and with the other two senior authors (18 and 19) to relate the themes to ongoing discussions in CSCW. Discussions with more co-authors grounded the themes more directly in existing theory and frameworks, bridging our inductive analysis with deductive concepts [15]. Ten days prior to the submission deadlines, all authors (including all knowledge-holders) received the manuscript and provided feedback on both the source material and themes, which are the basis of Sections 5 and 6 respectively.

4.5 Author Contributions and Positionality

The authors comprise a team of 20 people with Malagasy, American, British, Czech, and Canadian backgrounds. All authors contributed to the ideas present in the paper, and all but the last 3 authors contributed insight from field work in Madagascar. The first two authors, both American, recorded the field notes. Along with the first author, the last author, also American, coded and performed initial analysis of these themes. The other two senior authors (18 and 19) provided regular insight and editing to the first and last authors who drafted the manuscript. All contributing knowledge-holders were invited to be authors and given the opportunity to provide feedback on the manuscript. We acknowledge that despite our best efforts, the variety of cultures on the team likely caused power dynamics and communications differences during interactions, which may have resulted in the first and last authors not adequately capturing the perspectives of the knowledge-holders especially when these would have been critical of foreign or technology-based conservation interventions.

5 Findings

In this section, we present findings on conservation activities undertaken by paid workers across the three study areas in Madagascar. We organize these into three types of conservation programs that were common to multiple study sites: biodiversity monitoring, reforestation, and carbon sequestration. We also briefly comment on coordination processes that bridge the case studies. Each case study details the associated processes, local knowledge, technologies, and data, providing insight into the collaborative conservation processes and decisions across professional and geographic boundaries. We interweave a series of vignettes (italicized and indented) to ground the text in direct experience and center knowledge-holder voices. Additionally, we provide tables listing the local knowledge, technologies, and data we observed for each case study or for coordination. We refer to local knowledge as any insight, whether ecological, social, or otherwise, that a local community member knew from firsthand experience and leveraged for the success of the project. These case studies and tables demonstrate how complicated and interconnected these conservation program are, and that their success is only possible through capable local workers.

For narrative clarity, this section presents the point of view of F2A. All names are pseudonyms unless the knowledge-holder explicitly asked that we use their real name.

Table 1. Partial Table of Local Knowledge and their Applications Across Case Studies

Knowledge	**Application***
Tree phenology	Reforestation
Interactions between trees and animals	Reforestation
Fauna dependence on forest quality	Reforestation
Weather and climate patterns	Reforestation, Biodiversity monitoring, Coordination
Locations with good cell service	Coordination
Conditions for seedling survival	Reforestation
Landscape topography	Reforestation, Biodiversity monitoring, Coordination

**We did not observe local knowledge applied to carbon sequestration.*

Table 2. Table of Technologies and their Applications Across Case Studies

Technology	**Application**
Passive Acoustic Monitors (PAMs)	Biodiversity monitoring
Camera/video monitoring	Biodiversity monitoring
Radio collars	Biodiversity monitoring
Smartphones	Biodiversity monitoring, Reforestation, Coordination
FieldMap and SMART Mobile Apps	Biodiversity monitoring
Feature phones with cellular connection	Coordination
Standalone GPS	Biodiversity monitoring
Satellite imaging	Carbon sequestration
Computer vision	Carbon sequestration

5.1 Case Study 1: Biodiversity Monitoring

Biodiversity monitoring quantifies the diversity and abundance of species in each location, which are key metrics for conservation organizations. As Leila (MNP) described, “Biodiversity monitoring

Table 3. Table of Data and their Applications Across Case Studies

Observation	**Application***
Daily tree mortality	Reforestation
Species seen	Biodiversity monitoring
Species heard	Biodiversity monitoring
Staple food prices	Reforestation
Indicators of logging and poaching	Reforestation, Biodiversity monitoring
Rainfall, temperature, and other weather	Reforestation, Biodiversity monitoring
Tree biomass	Reforestation, Carbon Sequestration

**We did not observe data used for coordination.*

is at the heart of our work." Biodiversity monitoring was often implemented in conjunction with reforestation to measure success: species serves as indicators of forest health. All organizations were interested in quantifying species presence in a broad geography in a given month or season using a mixture of manual and automated data collection approaches, which we further describe in this section.

5.1.1 Manual Biodiversity Monitoring.

Tahina (CRS) and his biodiversity monitoring team set up their camp at the top of a ridge amidst old-growth forest. A four hour walk from the road, this site is their home for two weeks twice a year as they systematically take stock of the flora and fauna that inhabit the area. One evening, as the sun began to set, we joined Tahina and two other team members to conduct bird monitoring. As we approached the starting point of the three kilometer-long path on which we would walk, Tahina explained that we had to be quiet while watching and listening for birds. We reached the start of the monitoring path and the group immediately grew silent. Tahina started his watch and pulled out his bright yellow notebook, his camera slung across his neck. He quickly yet methodically wrote the English name and recorded metadata such as distance and orientation for every bird he heard or saw in neat columns (Figure 7). Twice he opened his "Birds of Madagascar" guidebook, but we felt it was more for our education than to help him identify a bird. As the fifteen minutes expired, he briefly conversed with his teammates in Malagasy to record the species they saw, but he made no notations and later told us that he had already recorded all those species. We continued on, repeating this process every 100 meters along the path. Hiking between sites, the team suddenly started pointing up into the tree canopy where we observed two troops of different lemur species. We spent about twenty minutes observing the lemurs as they shrieked, grunted, and clicked at each other and us. Later that night, we reflected that the team did not record any data about the lemurs and wondered if they enjoyed observing the lemurs despite the added time or if they were being thoughtful hosts for us, their foreign visitors.

CVB, CRS, and ESSA conducted biodiversity monitoring manually by following a formal process to estimate presence or absence of specific species. Sometimes this included measuring and recording data about the individual animal, such as its length or mass, but often it merely entailed recording the presence of a type of animal at one time and place. As described above, organizations cataloged birds and mammals by deploying three-person teams to walk along kilometer-long paths through the study area, stopping for fifteen minutes every 100 meters to make observations. For birds, the

team would record each one they saw or heard, using a notebook to record the species, how it was detected (sight or sound), where they observed it from, and its approximate distance and bearing from the observation spot.

> *Later that night, we joined Tahina's team in their work documenting mammals. We waited until the sun had set before walking to one of the paths near the campsite then watched as the team used powerful flashlights to locate any eyes that reflected light. When the team spotted an individual, they determined its species based on appearance and recorded the approximate location, group size, and time in a notebook. As with the bird monitoring, we stopped every 100 meters along the path searching for mammals. To record the coordinates, the team used a standalone GPS unit, as shown in Fig. 6a. We stood idly watching a team member painstakingly enter the interaction data into the GPS unit, which had only up, down, left, and right arrows, causing the process to take a few minutes for each entry. As we stood quietly observing, Tahina expressed his frustration at how time consuming it is to save information on the unit.*

Teams conducted this manual monitoring for birds, mammals, and reptiles along the same path repeatedly over multiple days, and for trees once in each location. Common across organizations, workers recorded the day and time, species, how it was observed (visually or audibly), the location of observation, and the distance and bearing from the observation site. The specifics of the location observation varied, sometimes using local human-made landmarks, such as trail blazes (i.e. "blue two yellow one"), and other times recording coordinates on a standalone GPS unit, as described above. Some teams also measured information about the observed individual, for example radiated tortoises' shell size as shown in Fig. 6b.

(a) The leader of the mammal biodiversity monitoring team recording notes after sighting a lemur near Ambodivoangy.

(b) A Bezà Mahafaly biodiversity monitoring team member showing the tools for radiated tortoise monitoring.

Fig. 6. Contextual figures for biodiversity monitoring in Madagascar

> *At another site, we accompanied Elias, joining him on his daily task of traversing the same 1.3km trail to look for signs of radiated tortoises. He walked us through his steps using the instruments shown in Fig. 6b, which help him measure and record each tortoise's location, shell width, mass, and ID number based on unique shell markings. We walked*

together along the trail but did not find any tortoises, which Elias explained was often the case during the dry season. He led us to a second trail to search further, which was the protocol if there were no tortoises on the first trail. Sadly, the second trail also lacked tortoises, so we returned to camp.

Several knowledge-holders working in Ambodivoangy demonstrated a similar process for monitoring trees when we joined them one morning. Having previously staked out 10 meter by 10 meter grids along their entire 1km path, the team returned to the plot they had left off the previous day and systematically documented the size and species of each tree above a certain Diameter at Breast Height (DBH) as well as the overall percentage of canopy cover for that plot.

Fig. 7. Tahina explaining the information he documents during a bird diodiversity survey.

5.1.2 *Digital Acoustic Recordings for Biodiversity Monitoring.*

After about three hours of conducting a bird survey, we returned to our campsite. We crowded around the cookfire-turned-campfire then unpacked the provisions we had hiked in with earlier that day, sharing them with the group as folks told jokes and stories. The most sought after items were chocolate bars, which we broke up and passed around, and toilet paper, which disappeared too quickly, especially with a few team members experiencing stomaching illnesses. We began discussing the 10 AudioMoths the team deployed for the duration of their time there and learned that Tahina analyzes the data manually by listening to the recordings over several months while simultaneously writing reports and conducting deskwork. When asked if he could identify the same birds from the recordings that he observed in person, he responded "I've only ever heard one bird," explaining that the recordings were often too quiet to discern bird calls from the background noise. Undeterred by the lack of useful information from one acoustic technology, he described his aspirations to purchase and deploy a Druid ULTRA bird tracker that he witnessed another team use to automate their monitoring program.

Several organizations TDARFAC, CVB, CRS, and LIFEPLAN, used acoustic recording devices to monitor biodiversity. The premise is to capture the audio of an area, either throughout the entire day or at specific times of day, to estimate the wildlife species present in that area. Tahina (CRS) explained that this method works best for birds and mammals, who tend to make the most audible, frequent, and identifiable vocalizations. Tahina and his team and the knowledge-holders at CVB captured a 14-day snapshot of an area, while TDARFAC and LIFEPLAN performed extended monitoring, gathering recordings for several months. Nomena (CVB) described that he wanted to conduct acoustic monitoring for extended durations but the limited memory card capacity and his desire to not overly impose on local community partners were prohibitive.

Although each organization followed a slightly different process for planning, measuring, and analyzing acoustic samples, they were similar enough to synthesize into a single flowchart, shown in Fig. 8. The process can be largely split up into three phases: preparation (steps A to C), recording (steps D to F), and analysis (steps G to O).

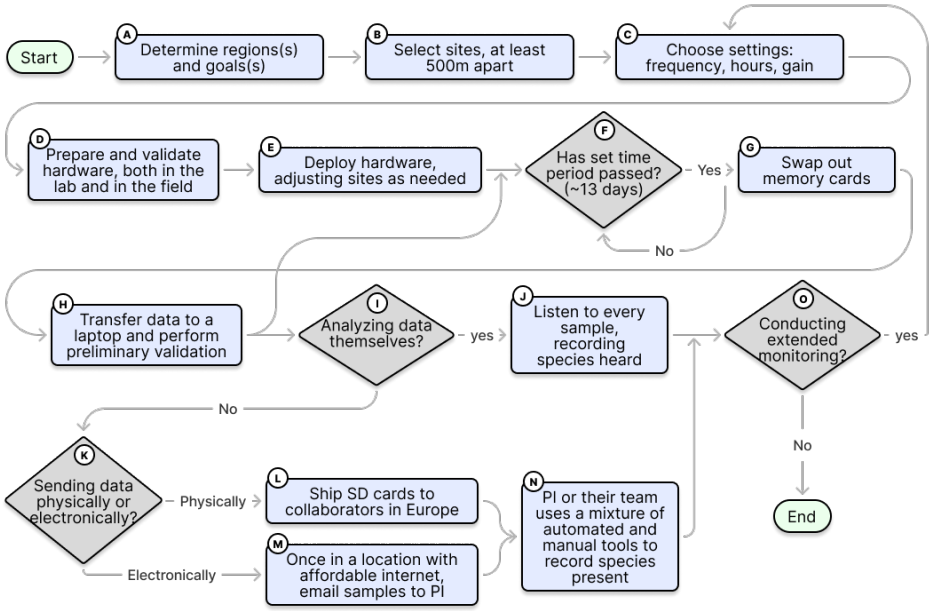


Fig. 8. Flowchart for acoustic biodiversity monitoring, synthesized across three organizations

For the preparation phase, all organizations focused on a specific region, although goals differed between identifying the presence of a single species to accounting for all present species. The selected sites were at least 500m apart from each other based on the range of the AudioMoth recording device, which knowledge-holders configured for specific frequencies, hours, and audio gain.

In the recording phase, knowledge-holders deployed acoustic recorders in the field, tweaking sites they established in the preparation phase to adapt to on-the-ground realities such as inaccessible locations. They swapped memory cards at regular intervals, for example every 13 days, to avoid saturating the cards' memory and to ensure against prolonged data gaps if the device malfunctioned. LIFEPLAN also replaced batteries at the same time, while TDARFAC waited until the batteries died. Jonathan (TDARFAC) described his meticulous process of labeling each memory card, placing it

in the proper storage container while in the field, and transferring the data to a laptop as soon as possible to minimize the risk of damage.

The analysis phase varied the most between organizations, with many organizations relying on external colleagues in other countries to perform data analysis. Tahina (CRS) described how he analyzed data locally, listening to all 1680 hours of audio in the background as he performed other tasks throughout his day. Jonathan (TDARFAC), explained how he would ride his motorcycle two hours back to his home in Antananarivo where Internet is more reliable and affordable, then upload and transfer the samples to an overseas graduate student who performs the analysis. Eliot LIFEPLAN conversely aggregates three months of data on microSD cards and then mails the them to collaborators in Europe.

5.1.3 Data, Technology, and Local Ecological Knowledge. Team leaders would often refer to data by its importance to the project and who would analyze it. For example, when checking in on AudioMoth recorders, Jonathan (TDARFAC) described how he was going to check up on "Tom's data," which would be crucial for evaluating "success of the reforestation effort." However, we did not hear field teams discuss specific findings about the data or get insights into the computational methods used for data analysis.

Knowledge-holders demonstrated much higher technology adoption in biodiversity monitoring than other conservation activities, leveraging tools to capture, communicate, and analyze data. In addition to audio recorders, ESSA used radio collars to track social and locomotive behavior of specific lemurs, and CRS's utilized trail cameras to identify a specific lemur species that was active at night and the FieldMap smartphone app to record and synchronize deployment information offline, as described below:

> *Tahina and his team members were determined to deploy a camera trap in a tree to confirm what species of lemur was frequenting the location to eat berries at night. While two workers repeatedly lobbed rocks with rope attached at a fork in the tree limbs, Tahina opened the FieldMap application on his smartphone to mark that point on the map and record the type of camera they were deploying. He explained that although he did not have cellular connection at the time, the app would synchronize with the cloud-based version when he could access the Internet. Once the other workers announced that they had successfully set the climbing line, Tahina focused on the climber who slowly worked his way up the tree with the Bushnell trail camera secured to his body. Tahina pulled out his personal camera to document the process, telling us that he mostly carried around the camera to capture the birds he encountered. Once the climber tested that the trail camera was configured for motion activation by repeatedly swinging around and waving his hands, he descended and we prepared to hike back to camp. Tahina gently placed his camera back in his padded bag, removing the detachable lens in the process. He briefly pulled out his clipboard to manually back up the information he documented in the app before leading our group to the end of the path that would take us back to camp.*

Knowledge-holders leveraged their place-based local ecological knowledge explicitly and implicitly throughout their biodiversity monitoring work. During our time shadowing Mr. C, Jonathan, and Daniel, we witnessed them choose where to place AudioMoth acoustic monitors by utilizing knowledge of relatively easy-to-access locations that were hidden from main trails and situated exclusively in the type of forest they were aiming to study. Jonathan explained his concern over "AudioMoth thieves" if the devices were too visible, necessitating knowledge of frequently traveled paths to avoid sites that are visible from them.

Weaving together scientific and local knowledge in concert with their American research team, they also optimized placement around where they could best hear species that indicate landscape

health. Mr. C, in particular, had learned from his several years working in the forest which species required various forest conditions. Thus, he and the team could use this knowledge to prioritize acoustic detection of species that indicate desired forest conditions or criteria. For example, because the mouse lemur is known as an "early colonizer" of native forests, the team placed the devices near routes that these lemurs were most likely to take. Presence of these species not only provided valuable biodiversity data but also served to evaluate the effectiveness of their reforestation program.

Finally, as described in the vignette, many knowledge-holders possessed key insight into animal sounds and appearances to easily distinguish them from each other. For example, although we observed the CRS team carry a reference book to identify birds, the team very rarely used it, instead going off memory.

5.2 Case Study 2: Reforestation

Reforestation aspires to promote a holistic approach to healthy forests. Although the specific success metrics are harder to quantify, in general they aim to promote forests with a complex mix of native flora and fauna to enable a robust ecosystem, especially by connecting habitats for critically-endangered species to expand their gene pools. Knowledge-holders described many benefits of native forests, including protection from erosion, resilience to adverse weather, and healthy food and water supplies for human and wildlife.

> *We met Nomena in his office at CVB, where he heads the Restoration Ecology Department. We spoke with him and his deputy Gaethon before and after our visit to the Ambodivoangy reforestation site they coordinated. As we stepped into their combined office for the first time, the babblings of the Ranomafana river audible through the open window, we were excited to discuss how technology might play a role in their restoration vision. Nomena explained their goals for reforestation with the surrounding community: (1) preserve the mountaintop forests, where farming is impractical, from logging and poaching threats, (2) implement agroforestry on the middle slopes where shade-tolerant cash crops like coffee and cocoa can grow together with native plants, and (3) work with villagers to implement sustainable farming practices in the valleys for the rice and cassava they grow for subsistence. Acknowledging the deep community knowledge about the land, he advocated for working together to integrate modern environmental data collection methods and actively "promote the long-term health" of the farmland. Reflecting on their mixed success, he explained how "tavy," the traditional practice of swidden agriculture[3], is not needed in their agroforestry approach. However, although most communities are buying in to the change, some community members are uncomfortable and "restless" with turning away from their traditional practices. Nomena aspires to measure crop yields in the future to demonstrate the success of their approach, but currently they deemed that locals lacked the financial skills to perform this analysis. Nomena also cautioned us to be careful if we designed any system around smartphone use, explaining that many Malagasy have "crayfish phones," which look similar to smartphones found in the Global North but often lack the full set of features, filling a niche between a smartphone and a feature-phone. Perhaps not wanting to undersell the potential for successful projects with local communities, at the end of our conversation Nomena took pains to emphasize how capable they are: "they don't have education, but they are smart. They remember things well."*

[3]swidden agriculture, sometimes called slash-and-burn agriculture or shifting cultivation, describes a broad variety of traditional and modern approaches to employing fire for agriculture. The authors prefer this term as it has a less loaded and violent connotation.

5.2.1 Reforestation Workflow. Fig. 9 documents TDARFAC's reforestation procedure supplemented with insights from CVB's approach. The reforestation process largely followed four phases: planning (steps A to E), preparation (steps F to I), planting (steps J and M), and monitoring (steps N to T).

> *On our last day in Andasibe, Mr. C (TDARFAC and MDI) led us on a hike through the landscape his team was actively reforesting, explaining his process for reforesting the area, one hectare at a time. He pointed out examples of invasive species that "drain soil nutrients", which his team cuts down three times a year. He expressed optimism that once the native trees re-establish themselves and provide sufficient canopy cover, he could decrease the frequency of these prunings. Although cursory views of the hilly green landscape suggested health to an uninformed eye, Mr. C pointed out large landslides and areas without lemurs to indicate the impact of non-native eucalyptus. The REDD carbon sequestration program had trained him and many others to plant trees that grew quickly, leading to vast areas of what the organizations' project manager Jonathan described as "shitty forest." He was now spearheading the effort to correct this failure.*

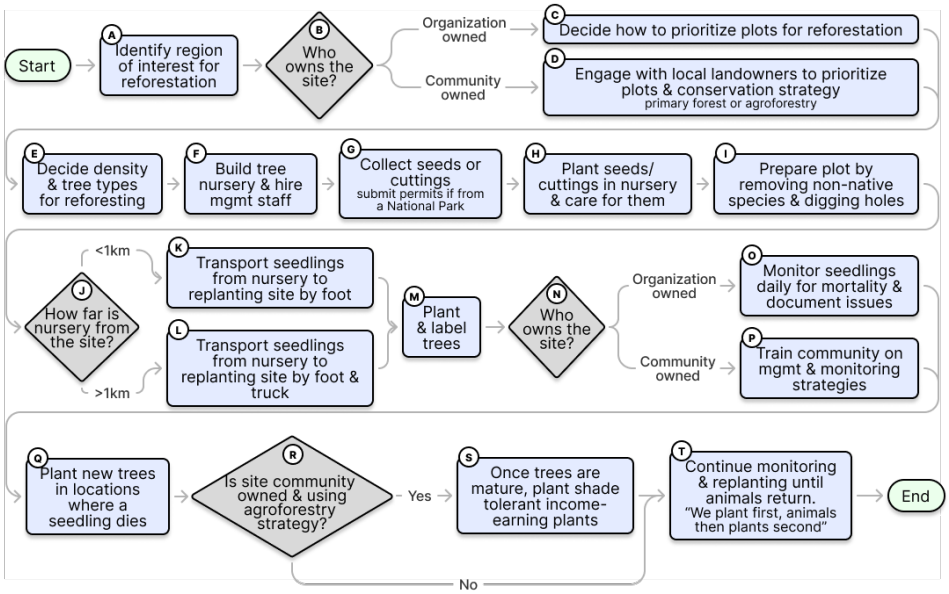


Fig. 9. Flowchart for reforestation, synthesized across two organizations

For the planning phase, knowledge-holders focused on reconnecting healthy forest that had been fragmented or extending the range of healthy forest further down mountainsides. The program near Andasibe owned the land and reforested it hectare-by-hectare, while the one near Ambidovoangy provided seedlings and training to villagers to implement agroforestry. Both programs built and staffed local tree nurseries from seeds collected nearby. Mr. C (TDARFAC and MDI) explained that they timed the seedling growth to be plantable at the November rainy season onset. He described how his team prepared the plots by digging holes and removing non-native plants, emphasizing his care to avoid removing native species and concerned that some of his team members were not experienced or careful enough to differentiate them from non-native plants.

> *Arriving at a plot that his team recently cleared of non-native species and planted with native ones, Mr. C described how they laboriously plant approximately 1200 trees by hand*

on each hectare, varying the types and distributions of trees based on Mr. C's knowledge of which species "call animals to come". He recounts spending time in "healthy forests," gathering seeds and observing how different combinations of species "get along". Suddenly altering his course to get a closer look at a sapling, he declared that it had died due to a combination of "long transportation" from the nursery and "dry soil." He noted the plot number, tree type, and cause of death in his notebook before describing how he would like to check each tree's mortality status every day but does not have enough trained employees. When we asked if more funding would solve the challenges of planting and monitoring so many trees, he paused and turned around to face the group. He scrunched up his face and described how he could not hire more workers because if he did, he would be "more alone." He had reached his capacity for the number of workers he could supervise and expressed anxiety about workers accidentally chopping down native trees. As our hike concluded, we asked whether drones could help automate some manual labor. "As long as my worker's jobs are safe", Mr. C responded.

In the planting phase, Mr. C's reforestation team transported seeds by bundling 20 seedlings together in a garbage bag and walking over the mountainous, vegetated terrain to their plots. Jonathan (TDARFAC) and Mr. C both commented that this stressful transportation "caused the most seedling death."

TDARFAC and MDI, followed a strict protocol for tree health monitoring, in which workers checked on each seedling daily, noting the likely cause if the tree died. The local project managers Daniel and Jonathan initially gave the impression that this high frequency of data collection was for scientific and conservation purposes, for example preventing future deaths with "smarter planting". However, in our later conversation with Dr. M, a project lead from an American university, she explained that the real motivation was to make sure workers performed the tasks often enough to remember how to do it correctly and to "create four to six more jobs than weekly surveillance." "And sure," she remarked, "it gives the added bonus of high-rez understandings of when seedlings are dying." Conversely, CVB's community-managed site implemented no formal monitoring, preferring to host trainings with community members and focus on planting shade-tolerant cash crops once the trees matured. Both organizations described replanting trees when one dies and how they hoped to achieve sustainability by leveraging nature. As Mr. C described, "We plant first, animals then plant second."

(a) A tree nursery in Andasibe.

(b) Recently planted tree seedlings

Fig. 10. Images of reforestation process in the Andasibe corridor.

Fig. 11 shows the flow of tree mortality data observed at TDARFAC from reforestation field-team members to a project PI. This collaborative work process is an extension of "paper-digital workflows" [29] in a Global South setting. In part A, paid members of the reforestation field-team who may not read or write walk through their assigned reforestation plots. For each tree that appears dead, they remember the identification number and investigate a likely cause of death, communicating these verbally in Malagasy to the leader of the reforestation team. The leader aggregates this information from all team members, recording them in a notebook in Malagasy and French. The project manager photographs these notebook pages, which they later translate to English and input into a laptop at the research station. Finally, the manager digitally sends these data to a project PI, who is often located abroad. As such, we describe this process as a "verbal-paper-digital" workflow.

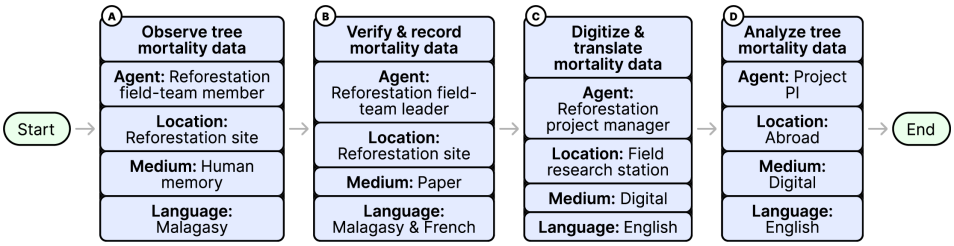


Fig. 11. Flowchart for the translation and digitization of tree mortality data

Unlike biodiversity monitoring, we observed minimal digital technology in reforestation, only witnessing Jonathan and Daniel using their phones to take pictures of notebook data and later computers to transmit these data overseas. Almost every knowledge-holder used their phones to coordinate activities but not directly for reforestation work.

5.2.2 Data, Technology, and Local Ecological Knowledge. Because they did not use monitoring technology for reforestation, knowledge-holders collected all data manually at first and digitized it later. The majority of data we observed pertained to tree mortality: the plant number, plot number, tree species, planting date, altitude, seedling height at planting, slope, aspect, coordinates, and date of seedling death. The organizations working at all three sites also recorded data that indicate potential pressures on the forest. For example, in coordination with COBAs and VOIs, Tahina recorded slash marks on trees and other signs of logging during their Ambodivoangy biodiversity monitoring expedition. In the three communities around Bezà, Edino recorded staple crop prices to predict economic hardship, which in turn increases pressures to log or farm in protected areas. At 7 a.m. every day, Edino also collected precipitation and temperature data by hand using a manual rain gauge and thermometer.

Local knowledge played the central role in Mr. C's decisions on which trees to plant. Out of over 1,000 local tree species, he prioritized 60 of them for reforestation based on their direct benefits and which ones "get along". To maximize impact, he selected trees that provide sufficient food sources for lemur and other species, co-locating plants with complementary life-cycles that would collectively provide food year-round. LEK similarly drove TDARFAC's decisions around planting locations and densities, as the team tried to "mimic species that occur together naturally" in different parts of primary forests– mountaintops, slopes, valleys, and beside bodies of water. Knowledge of changing weather and climate patterns informed when to plant, and for CVB's reforestation programs centering around agroforestry, common local knowledge of which trees would provide sufficient shade for cash crops like cocoa and coffee was crucial decision making.

Edino's knowldge of local social and economic trends allowed him to translate crop prices into forest pressures. He explained how both low and high prices caused financial stress for the surrounding farming community, but only high prices were a sign of potential danger. Low prices likely meant crop surplus, so though folks may not be able to make a profit they would have plenty of food and therefore not turn to the forest for income. However, high staple prices often indicated crop failures and therefore a higher chance of unsanctioned logging or poaching. Edino's insights were nuanced, requiring contextualization in local trends and history, showcasing how important local understanding is for conservation. Additionally, he relied on local familial connections to gather this information quickly, for example calling his sister to get price data from the next town over rather than spending a day traveling there himself.

5.3 Case Study 3: Carbon Sequestration

Carbon sequestration describes the process of long-term carbon storage in some vessel, in this case trees and other biomass, to reduce the amount of carbon dioxide in the atmosphere. It can entail both conserving existing forests and restoring forest ecosystems to rewilded prior states [3]. These programs receive funding from non-profit and for-profit organizations and have faced scrutiny for not considering local land claims and thus causing social tension over land privatization and multi-use arrangements [103]. We encounter an example of this tension in Andasibe between new landowners and locals who have traditionally farmed the region. Foreign conservation funding has increased the effective value of the land, forcing subsistence farmers to implement their traditional fire-based farming practices elsewhere. We also encounter and additional tension around the lack of sustainability in carbon sequestration payments- a one-time purchase is meant to sequester that carbon forever, but workers need to maintain that carbon stock for it to count. We witness this in the difference between Figs. 12 and 13, where one-time and undependable payment structures disincentivize locals from maintaining the sequestration forests. This reliance on funding sources from foreign governments and organizations whose priorities can change on a whim highlights a broader fragility within conservation and conservation technology. Funding, technology access, and ease of travel can change rapidly, for example through the reduction of USAID funding, import tariffs, threatened cutoff of Starlink, and immigration policy.

5.3.1 Historical Carbon Sequestration . We did not witness any programs that focused on carbon sequestration, but knowledge-holders in Andasibe, Ranomafana, and at the Madagascar National Park office discussed historical and ongoing programs. Three Madagascar National Parks have had the ability to sell carbon credits since 2012. Knowledge-holder commentary on carbon sequestration programs and associated technologies was largely pessimistic, describing the negative consequences of centering sequestered carbon over broader ecological impacts. Further, Mr. C shared a story about a failed carbon credit initiative that we share here, synthesized from knowledge-holder accounts and a published article [102], as an insightful example of a failed conservation program in a Global South setting.

The World Bank funded this carbon credit and sequestration project, which Conservation International (CI) implemented through a foreign researcher who provided training to Mr. C. and other community leaders. They learned planting methods to optimize tree density and species composition, later training hundreds of local people to administer the program. CI provided trees which locals planted on their own land in exchange for the promise of money that would be generated from carbon credits. Locals planted the trees beginning in 2003, yet by 2005 there was still no money from the credits. Additionally, because the funds were focused solely on planting trees rather than tree maintenance or the development of sustainable alternative livelihoods, people had no other means to make money. Mr. C described how many people cut down the trees to

plant crops that could sustain their livelihood and produce charcoal for cooking. Mr. C regarded the project as a failure, and it clearly weighed heavily on him, as he brought it up frequently during our conversations. He relayed his childhood dream to reforest the land and conveyed his deep sadness at its failure. However, he learned from these shortcomings to ensure that his organization has ongoing funds for tree maintenance and prioritizes long-term employment. We provide representations of both the intended and actual processes in this sequestration program in Figs. 12 and 13. They are notably less rich than the other case studies as they draw from descriptions rather than observations.

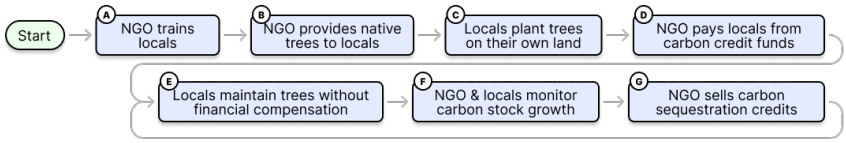


Fig. 12. Intended process for using forests to sequester carbon.

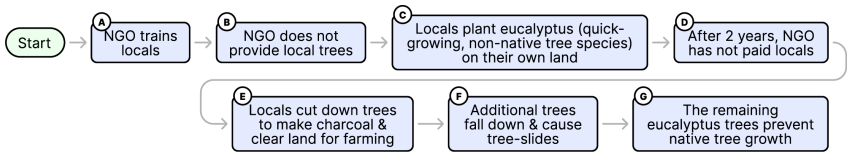


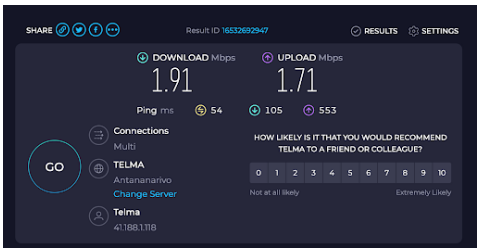
Fig. 13. The actual events of a failed process for using forests to sequester carbon.

5.3.2 Contemporary Carbon Sequestration . Contemporary programs still aim to sequester carbon, typically relying on digital technologies to automate parts of the process. Both Nomena and Dr. M described satellite imaging systems that classify the percent of land that is forested, which organizations use to justify the creation of carbon credits. Both knowledge-holders criticized this approach due to its inability to differentiate between native and non-native vegetation, which has implications for both ecosystem health and sequestration duration. We did not hear knowledge-holders describe applications of local knowledge to carbon sequestration programs, which centered on western conservation methods and the singular goal of storing carbon rather than local methods to promote broader ecosystem health.

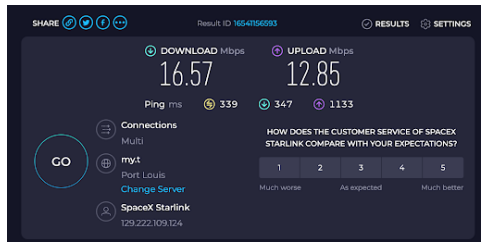
5.4 Underlying Coordination

Nomena joined us in the car for our ride to the trailhead to Ambodivoangy, helping us buy provisions and secure porters for our expedition. As we bounced over potholes, he asked with a glint in his eye if we had heard that his office research station had upgraded from wired Internet to Starlink the night before. Indeed we had heard and had taken speed test measurements, documented in Fig. 14 directly before and after. We noted a roughly nine times increase in download speed to 17Mbps and a comparable increase in upload speed to 13Mbps but a six times increase in roundtrip time. This jump in bandwidth not only improved the experience of the 30 people reliant on that Internet access, but Nomena also mentioned that it also saved them substantial money. Previously, the sole company offering Internet to their somewhat remote station was Telma, who had been charging roughly $1,000 USD monthly versus $50 monthly for Starlink. Nomena continued, sharing his hope that Internet that was more affordable and more flexible would fix fieldwork

challenges such as coordinating logistics or checking in with his family. In a prior field site, he had gone so far as to rig up a "phone tree" on an especially tall Tamarind tree, using a drawstring bag and a pulley to queue up messages before hoisting his phone upwards to a spot where it could connect to the celltower.



(a) Ookla speed test results when the research station was still using fixed Internet provided by Telma.



(b) Ookla speed test results after the research station transitioned to Starlink. Taken on the same device at the same place and time of day.

Fig. 14. Speed test results from CVB's research station before and after they switched to Starlink.

Knowledge-holders described their use of technological and manual processes to communicate and coordinate conservation activities, bridging different conservation programs and the workers' professional and work lives. We have largely left these activities embedded in the case study where we observed them, but offer the above vignette to highlight how central coordination and communication were to the success of these conservation programs.

6 Discussion

In this section, we analyze conservation technologies in Madagascar through extensions of an assets-based design framework and uncover insights into design considerations. Specifically, we advocate for: A) a re-evaluation of how conservation technology sustains community assets it relies upon, and B) a contextual re-framing of what a conservation technology's goals should be. In this analysis, we examine four themes: 1) local knowledge 2) love of nature, 3) economic sustainability, and 4) local autonomy. For each of these four themes, we define the concept through examples from our case studies, describe tensions in their incorporation, and provide design considerations for their implementation.

6.1 Theme 1: Prioritizing Local Knowledge

As the findings demonstrate, local knowledge, primarily in the form of local ecological knowledge (LEK), is central to conservation success. Knowledge of the fruiting timeline of different tree species helped decide what mixture of trees to use in reforestation. Insight into which forest plots were easy to access but not visible to passersby informed acoustic sensor deployment locations. Even knowledge of where one could get adequate cellular service played a central role in coordinating programs and ensuring safety.

Additional knowledge about local context, meaning the multiple dimensions of conditions and processes in which a technology will be used [20], is similarly crucial to success. For example, AudioMoths, designed with biologists using a human-centered design approach [122], proved useful in biodiversity monitoring for three Malagasy organizations. However, because it was not designed for specific use in Madagascar, knowledge-holders made modifications, using tampons for waterproofing and replacing batteries more often than necessary because they lacked an easy

way to view battery status. We do not suggest that AudioMoth must design for every user group, but rather to highlight the importance of incorporating local context, particularly in communities that are not represented in the design team, when designing conservation technologies. To achieve sustainable success, designers need to both support workers' acquisition of LEK and incorporate the context in which workers apply the technology. To consider a technology's obligations to the assets it is founded on, we draw upon the principle of reciprocity prevalent in Indigenous value systems: "humans have a responsibility to reciprocate for all they have been given" [66]. Just as humans have a responsibility to reciprocate benefits with each other and with non-human beings, to be grounded in sustainable practices they must also reciprocate benefits with the assets they use.

6.1.1 Tensions: Local Knowledge. CSCW researchers have previously acknowledged local knowledge as an asset within participatory design frameworks [145]. However, in the context of conservation programs and research much LEK acquisition serves as an instance of "invisible work" [131]. In addition to other forms of invisible work we observed such as maintaining remote field stations [115] and shipping SD cards, knowledge-holders' labor gathering LEK is not widely acknowledged in prior HCI work compared to the attention paid to foreign researchers. Star and Strauss offer design principles to address invisible work, the most relevant here being to ensure that "requirements analysis and specification of the system" accounts for the "tradeoffs and balances" of visible and invisible work [131]. Applied to conservation technology, this entails ensuring that the technology designer accounts for the invisible work necessary to enable the system to operate.

We also saw that the analysis work performed by scientists, especially when they are based abroad, is similarly invisible to the Malagasy workers. For example, Eliot, the project manager at LIFEPLAN, oversaw the collection and mailing of acoustic monitor SD cards from Madagascar to a European university for analysis. Although he knew how to manually analyze the data and operate the acoustic monitors, he did not have much insight into how the European university was automating the analysis of the acoustic data. Using technology to facilitate understanding the usage context of all system stakeholders, such as Eliot, the data analysts in Europe, and Malagasy field workers who are even further removed from their European partners may help to address this two-way invisibility tension.

We also observed how introducing technologies without incorporating knowledge of the local context, can "reinforce existing modes of oppression and introduce new ones" [69]. For example, the carbon credit programs failed to account for the importance of biodiversity to local ecosystems and communities. When the World Bank program failed, communities who had prioritized planting eucalyptus trees had to perform additional unpaid work to restore native habitat that would allow their ecotourism-based local economy to flourish.

6.1.2 Design Considerations: Local Knowledge. We advocate for technology design to *sustain* rather than merely *leverage* community assets, in this case LEK. If a conservation technology relies on LEK, it has a minimum responsibility to avoid diminishing a LEK, for example by reducing opportunities for workers to spend time outside. Ideally it will actively bolster and facilitate local ways of knowing, contributing to a sustainable virtuous cycle of reciprocity. Because colonization is a main driver in the loss of local ecological and Indigenous knowledge [84], designers should draw from post and decolonial computing theory [2, 27, 53] and consider the importance of LEK when creating technologies for its preservation. Importantly, LEK should not be viewed as something to be extracted from knowledge-holders [53], but rather a unique asset to be promoted within a local community. Despite recent research initiatives to design for LEK and Indigenous knowledge [46, 78, 104], there remains a dearth of design approaches that are built for or by Global South knowledge sources. Thus, there is a huge opportunity for CSCW and HCI researchers to

identify, develop, and share design practices that can amplify the local ecological history and knowledge that are essential to biodiversity conservation [78, 80].

Practically, designing technology that sustains LEK largely entails providing opportunities for workers to engage with their community and surrounding natural environment through their work, for example by only partially automating the data pipeline and strategically leveraging workers to scale up impact. For instance, a new acoustic monitoring technology could upload metadata, such as memory usage and battery level, to a platform that workers can access on the Internet. They could use this information to prioritize what devices to revisit, allowing them to support more devices while sustaining their LEK through field visits. Another example of technology sustaining LEK is facilitating workers paying more attention to their environment. Imagining a smartphone app to record the mortality status of trees in a recently reforested area, the app could be designed to prompt the user with questions based on a decision flow from their prior responses. More experienced knowledge-holders could inform the workflow, for example by prompting a user who sees a dead Calophyllum tree to look for signs of the wilt fungal disease. Less experienced knowledge-holders would be encouraged to pay attention to aspects that more experienced knowledge-holders have identified as important, facilitating the transfer of LEK. Conservation technology could also facilitate two-way visibility, for example by designing a web application that both reports the status of acoustic monitors and outputs the analysis of the SD card data. Field workers who log on to track when they need to swap SD cards could have the opportunity to visualize the species present on the SD card they mailed 3 months ago, provide field observations that may explain the change in species seen, or otherwise connect with the people performing analysis on another continent. A better understanding and appreciation of the work each team member performs could provide new insights, increase motivation, and improve overall worker wellbeing.

6.2 Theme 2: Fostering Love of Nature

As with local ecological knowledge, we saw how essential knowledge-holders' love of nature is in ensuring the long-term success of conservation programs. Mr. C described his excitement in being able to finally reforest his homeland properly after prior unsuccessful attempts. Tahina carried his personal camera with him on every biodiversity survey, demonstrating a deep appreciation for birding that contributed to his efficiency and thoroughness in conducting bird biodiversity surveys. Jonathan described the potential impact of love for nature when pitching a video game where the player experiences life from the perspective of a lemur, musing "if they love it, maybe they will protect it." These findings align with recent conservation research, which contends that recognizing the intrinsic value of nature is a "vital aspect of conservation of the biosphere" [106]. Additional research has demonstrated the beneficial impacts of strengthened connections with nature both among professionals [71] and volunteers [47] in conservation spaces. Thus, love for nature is clearly an asset for natural ecosystems and conservation programs, and should be supported and elevated by any associated technological interventions.

6.2.1 Tensions: Love of Nature. Specifically within SHCI, researchers have examined how digital technologies can increase locals' appreciation of the environment and natural resources, leading to enhanced stewardship [117]. Similarly, Webber at al. found that digital technologies in natural contexts can promote "deeper engagement and closer observation" but also "distract people from enjoying nature directly" [141]. This juxtaposition may arise based on a user's pre-existing love of nature before using the digital technologies, yet more research is needed to determine 1) how to reach users who have different levels of existing love of nature and 2) how to design technologies that minimize the risk of distracting users from their natural surroundings.

6.2.2 Design Considerations: Love of Nature. Because conservation programs benefit from workers' love of nature, they should also aim to foster this love through technologies that they introduce. Based on prior works that use technology to promote engagement with nature in zoos [99] and woods [116], we propose that designers facilitate location-based experiences and present audio and/or visual recordings of species in the area that are difficult to find or clearly identify. For example, if designing an app to help workers monitor tree mortality through manual observations, designers could integrate the capability for workers to tag and share beautiful landscapes or captivating species they observe in the area. Additionally, designers can explore the gamification of audio-visual data collection to instill passion and curiosity, i.e., by tracking which species workers have observed out of all the species they might expect to see in the area. Apps such as Seek by iNaturalist[4] already perform this task but are geared for citizen scientists, revealing the need for such design interventions made for conservation workers and other audiences.

Many design considerations that can foster love of nature are not directly technical, raising a potential design tension in a space where efficiency is often valued above other goals. We contend, however, that designing technologies that give workers time and encouragement to note and appreciate the species and spaces around them can help conservation programs build a capable, long-term workforce. Additionally, such technologies can help to grow local ecological knowledge, another asset that must be designed for and nurtured. We acknowledge that design features alone are unlikely to facilitate deep connection with the environment. Designers should avoid romanticizing workers' lives and motivations, remaining mindful of potential exploitation when working across power dynamics [76]. Rather than imposing personal values through technology, designers—working collaboratively in an assets-based approach—should support systems that enable users to continue strengthening the values they hold.

6.3 Theme 3: Centering Economic Sustainability

Compared to many Global North contexts in which technology serves the goal to automate what people do, freeing them up to perform other tasks, we observed that knowledge-holders valued conservation programs that increased opportunities for local workers. In fact, conservation was so central to the local economies around Madagascar's protected areas that it would be counter-productive and detrimental to replace people with technology in many scenarios. Dr. M, when explaining why their reforestation program conducted daily manual tree mortality checks despite the lack of scientific need for such granular data, explicitly described the creation of additional jobs as a primary benefit. Similarly, Mr. C's first concern when we asked whether drone imaging may help improve the organization's biodiversity monitoring was, "as long as my worker's jobs are safe." Edino even invested several days each week gathering price data from nearby village markets to gain insights into a community's economic health because of its centrality to conservation. Reliable employment and income within Malagasy communities reduces environmental stress and promotes conservation in surrounding natural spaces [51]. Therefore, conservation technologies must align with the economic realities of the places they are deployed.

6.3.1 Tensions: Economic Sustainability. Most SHCI works focus primarily on environmental sustainability [48], marginalizing the economic component within the three pillars of sustainable development [84, 124, 128]. Conservation technologies must consider this economic angle to authentically "achieve or preserve sustainable ways of being" [11]. Most prior SHCI works neglect the importance of financial sustainability in conservation technology design, which causes technological interventions to fail when they do not align with funding structures, economic values, or employment goals of the communities in which they are deployed. Development organizations

[4] https://www.inaturalist.org/pages/seek_app

and local communities in Madagascar already understand the tie between economic health and sustainable conservation. In 90% of 611 interviews with Malagasy stakeholders of social benefit livelihood projects, subjects identified "specific conservation goals" associated with the program, aligning with the secondary goal stated by project designers of "decreasing pressure on forest" [51].

Another tension arises because the economic goals of a local community maps more clearly to a need than an asset within the assets-based framework. Aspirations-based design offers insight here, where aspirations differ from needs in that they represent a "positive life change" and are more consistent over time [134]. Employment goals align well with this categorization of aspirations and offer design insight in that they can be readily operationalized [70, 134]. These works primarily frame aspirations as personal, for example "I want to be able to buy my own home," but they provide a framework for also considering community goals, for example "we want this conservation program to create five new year-round jobs." In the aspirations-based design framework, technological interventions "play a support role" in facilitating long-term flourishing rather than being the ends themselves [134]. The shift from individual to community goals further underscores the need to understand the community and emphasizes that any technology is part of a broader socio-economic system.

Another useful way to handle the tension of economic opportunity is through the lens of Appropriate Technology, which is predicated on designing solutions in Global South contexts from the ground-up rather than altering solutions from the Global North [123]. In its focus on solutions that are compatible with the resources a community has available, it emphasizes labor-centric approaches over capital-centric ones. Appropriate Technology acknowledges that local labor is a powerful resource and that employing these people is advantageous to automating their jobs away. An assets-based approach can address Appropriate Technology's shortcoming of defining what constitutes "appropriate" [9, 100] by centering local communities. The workers and leaders in communities engaged in conservation activities possess insight into both what approaches are feasible and which align with community aspirations.

6.3.2 Design Considerations: Economic Sustainability. Conservation technology can support local economies by designing systems that align with and value local workers. Rather than assuming that automation best serves the conservation goals of a program, designers should carefully consider what roles technology can play that are complementary to roles humans excel at. One design recommendation is to prioritize technology development that provides metadata and status information to conservation teams so that they can best use their limited human labor. Eliot (LIFEPLAN) expressed enthusiasm during discussions about retrofitting acoustic recorders with wireless transponders to provide regular updates on battery life, SD card space, and eventually the number of species detected once they roll out their AI detection models. The employed Park Rangers would still be central to data recovery, but they would be able to better prioritize their tasks. Another way to design technology to support economic opportunity is to prioritize systems that scale up what people can do, making local labor more valuable. For example, designing a companion app that allows biodiversity monitoring teams to more quickly document the species present in an area by integrating trail camera images and manual observations could make it feasible to conduct continuous biodiversity surveys in an area rather than once or twice a year. This would make biodiversity monitoring technicians more valuable and present opportunities to monitor a greater number of sites. Finally, advancements in artificial intelligence presents opportunities to both employ and train workers, although care must be taken to not supplant them. Carbon sequestration is notorious for inaccurately estimating the forest contents and thus the quantities of carbon stores, but this shortcoming could be addressed by designing a system that relies on local workers to regularly gather reference data.

6.4 Theme 4: Embracing Local Autonomy

We saw that knowledge-holders consistently eschewed the "one-stop-shop" approach to using tools, preferring to rely on a diverse set of redundant methods and resources to record data and perform their conservation tasks. Embracing the autonomy of local knowledge-holders means working within this paradigm, often embracing a hybrid approach of digital technologies, non-digital tools, and human assets to accomplish a task. At a single location over the course of one hour, Tahina used his smartphone-based FieldMap application, clipboard, notebook, personal camera, trail camera, extensive bird knowledge, and local trail knowledge to record biodiversity information. The "verbal-paper-digital" workflow in Figure 11 also captures the many modes and methods that a single organization uses for observing, recording, communicating data. The increasing power and communication infrastructure in Bezà allowed us to more dynamically interact with the outside world, but we observed that knowledge-holders always had a plan in place before they embarked so that they would still be okay if the infrastructure failed. Technology presents a major opportunity to streamline these workflows, but the system can become fragile if it places too much responsibility on any single technical component and removes the ability of locals to make decision. Designers must account for the drawbacks of top-down, centralized approaches that dictate the entire workflow, focusing instead on organic solutions that are compatible with local decision-making.

6.4.1 Tensions: Embracing Local Autonomy. The Appropriate Technology framework emphasizes that technologies in Global South settings should support local autonomy and decision-making [123]. Local autonomy is central to sustainable interventions, with studies indicating that local input and direct grants reduce negative impacts of agricultural interventions while leading to "substantially higher adaption two years after the intervention ended" [24]. The reasons that a given technical approach may falter are varied, but we observed some common pitfalls that suggest hybrid approaches that prioritize local autonomy are more robust for aiding conservation in Madagascar and similar contexts. One tension we observed was the imbalance of resource access both between nations and between regions within Madagascar. Our findings highlight a dichotomy between conservation technologies in Global North and Global South settings, similar to recent work noting the "asymmetric distribution of resources, expertise, equipment" [78] for ecoacoustic monitoring in Ghana. Knowledge-holders in biodiversity monitoring programs from both Andasibe and Ambodivoangy expressed frustration at deploying audio-visual monitors, with long lead times for SD cards causing sensors to sit in offices unused and the unavailability of tampons for waterproofing in Madagascar forcing a knowledge-holder to fly with one whole suitcase just to transport tampons. Similarly, LIFEPLAN sent their SD cards abroad for analysis due to a lack of adequate computing infrastructure and analytical training in Madagascar, a trend that has been seen in other global, collaborative work settings [29]. Technology design that centers autonomy, uses locally available materials, and supports local analysis would increase the scale and speed of biodiversity monitoring.

We also observed disparities between knowledge-holders from Madagascar. For example, all field team leaders spoke and wrote fluent English and owned cellphones while field team members rarely spoke English or owned cellphones and sometimes had minimal Malagasy literacy. These nuances of mismatched resources serve as a reminder that Global South communities and partner organizations are not monoliths. Thus, community or partner engagement can authentically materialize in many different things, even in the context of Madagascar-based conservation organizations. Technology design should not stop at catering to the goals and autonomy of just the project managers but strive to achieve goal alignment and decision making among all team members, especially those with the least privilege and who are often the hardest to reach.

We noted that knowledge-holders and communities in Madagascar had the perception of Global North technologies and programs being superior, similar to prior work revealing that some Global

South communities prefer the technologies that Global North researchers favor [30]. In fact, Jonathan regularly described anything designed at a specific U.S. institution as "better technology" he wished to use, even if the technology was not designed for applications within his job. Furthermore, several Malagasy knowledge-holders noted Malagasy leaders' deference to foreign insight over local expertise and described how their only path to being taken seriously in Madagascar was to earn an advanced degree from outside of Madagascar. Jonathan, who holds a master's degree from a Malagasy university, described how the Malagasy education system "trains us to be research assistants, not researchers," an observation that Daniel, a Malagasy-trained veterinarian, nodded his agreement to. They both were contemplating further education abroad. This perception that foreign technology and education are superior presents a challenge to autonomy, discouraging knowledge-holders from thinking they have the skills or material resources to undertake robust conservation programs. Assets-based design can help to counter this perception by highlighting and celebrating the unique assets that Malagasy communities possess .

6.4.2 Design Considerations: Embracing Local Autonomy. Many successful technologies already center local autonomy, striking a balance between specificity and generalization to adapt to local goals and constraints. For example, we saw AudioMoths deployed at three different sites, each with different workflows but aligned in their use for biodiversity monitoring, indicating that the technology is attuned to the challenges and goals shared by many locations while offering flexibility in its integration. To avoid reliance on materials that are hard to source in-country, conducting prototyping and design in-country with the materials available in local stores and markets can ensure sustainable supply chains. For instance, prototyping a smartphone app with locally available "crayfish phones" ensures that operating systems and Bluetooth versions are compatible with the technology stack. For devices that are not readily available in country, designers should consider approaches that make repair possible and system replacement unlikely. LIFEPLAN manually replaced broken AudioMoth microphones by soldering them in their Madagascar lab space rather than ordering new ones, a process that was facilitated by AudioMoth opensourcing their hardware design. Although SD cards were hard to find, cellphones were readily available and may be hackable to provide similar functionality. Finally, we advise applying the "Keep It Small and Simple" [7] approach not just to design, but to overall system goals and processes. For example, if designing a system to improve reforestation outcomes, technologists should focus on the biggest pain point, which appeared to be sapling death during transportation from the nursery to the planting site (Fig 9 steps K and L).

7 Limitations and Scope

We acknowledge that the F2A's limited time in Madagascar and exposure to only three of the numerous conservation programs across the country limit the applicability of our findings and design considerations. We attempted to address these shortcomings by engaging with knowledge-holders as co-authors, which in addition to acknowledging the value of their work ensures that the research we present here is affirmed by people with countless years living and conducting conservation work in Madagascar. Future work should aim to further break down communication and power barriers by using longer-term technology probes and user diaries [21]. As our discussion describes, assets-based design of conservation technology in a place like Madagascar is inherently tied to understanding the contextual goals and challenges of numerous stakeholders. This nuance makes it impossible to provide exact design recommendations that work in every context, instead favoring approaches and considerations that give a project a greater likelihood of sustainable success. Impactful future work would engage with more locations and conservation organizations

across Madagascar and other biodiverse regions in the Global South, more deeply exploring the similarities and differences across these ecological, cultural, and economic boundaries.

Based on observations from academic literature and the authors' firsthand experiences, we expect that these findings and design considerations have value in contexts outside of conservation programs near Madagascar protected areas. Aligned with the four themes from the discussion section, this paper will have the most direct applicability to places and conservation programs that engage heavily with local communities and their knowledge, have value systems that cherish nature, are situated in regions whose economies center around relatively low-wage manual labor, and where access to resources available in the Global North is limited. This description applies to many but not most settings in the Global South and may apply differently to organizations working in the same physical space. Specifically, we contend that these approaches are relevant in other "biodiversity hotspots" that collectively represent 43% of endemic animal species [52], "like-minded megadiverse countries" that collectively hold over 60% of the world's biodiversity [96], and countries with a similarly high percentage of publications led by international authors. Furthermore, these insights offer value to conservation programs in the Global North that aim to authentically engage with local communities and foster approaches that are sustainable in all senses. Contributing to conversations around users sharing preferences across contexts' [105, 147], we contend that many of our findings, for example the preference of knowledge-holders to reuse or repurpose existing technologies, resonates with challenges in the Global North- "not all stakeholders in ecological management are early adopters" [80]. Additionally, Global North countries such as the United States and Canada have Indigenous populations with significant levels of LEK that must be preserved and promoted [17].

8 Conclusion

Any sustainable intervention must consider its impact on sustaining community assets, such as local knowledge and appreciation of nature, and centering community goals, such as employment opportunities and local autonomy. align with both community assets (knowledge, social connections, physical infrastructure) and goals (conservation, employment, acquisition of LEK, building connections with the land). Through the context of local conservation workers around protected areas in Madagascar, we explore assets-based design's ability to illuminate community goals, specifically around economic opportunity and autonomy, and further sustain assets, specifically local knowledge and love of nature. This paper's contributed case studies, emergent themes, challenges, and design considerations extend components of assets-based design to conservation in the Global South and illuminate the tensions when striving for authentically sustainable conservation programs. The synthesis of our qualitative approach with literature from CSCW and related fields centers the importance of local workers and their local knowledge for successful stewardship. This work promotes the co-creation of equitable conservation technologies and has applications to the many settings where local workers and knowledge play a central role in sustainable conservation.

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