

45 **Summary**

46 The choice of how to monitor conservation and restoration is not solely technical – it
47 shapes which outcomes are valued, whose priorities define success, where resources flow, and
48 who benefits. The shift toward tech-based monitoring, driven by demand for scalable metrics,
49 risks incomplete ecological understanding, sidelining Indigenous Peoples and Local
50 Communities (IPLCs) from data ownership and decision-making. In a new analysis of 130
51 reforestation organizations, we show that market-based organizations cite remote sensing
52 nearly 50% more often than mission-based ones, a gap that has widened over two decades.
53 Adoption is outpacing the evidence that tech-based methods are cheaper or more accurate than
54 traditional ground-based approaches. We offer targeted recommendations for researchers &
55 research institutions, policymakers, and project developers & standards bodies to keep
56 monitoring locally led, ecologically grounded, and economically just. As conservation and
57 restoration scale, how progress is measured shapes whether efforts deliver lasting ecological
58 gains and benefits for IPLCs, outcomes technology alone cannot capture.

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79 **Introduction**

80 The success of efforts to conserve and restore the world's ecosystems is increasingly
81 measured using technology: satellites tracking vegetation cover, drones mapping structure in
82 three dimensions, recorders listening for wildlife, and DNA extracted from soil and water. Yet
83 which of these tools an organization adopts reflects not only what a landscape needs, but also
84 how its work is funded. Advancing ecologically effective and socially just conservation and
85 restoration depends on centering equity and ensuring that local land stewards lead (Sterling et
86 al. 2017, Höhl et al. 2020). This extends to how project outcomes are monitored (Evans et al.
87 2018), as conservation and restoration are inherently socio-ecological endeavors (Egan and
88 Estrada 2013).

89 Beyond its moral imperative, equitable approaches improve conservation and restoration
90 outcomes and are a strong predictor of project longevity, as Indigenous Peoples and Local
91 Communities (IPLCs) are more likely to sustain projects they benefit from and have agency over
92 (e.g., Erbaugh et al. 2020, Djenontin and Zulu 2021, Mansourian and Sgard 2021, Elias et al.
93 2022, Löfqvist et al. 2023b). Decisions about what is monitored, and how, shape project
94 outcomes and how landscapes are transformed. While equitable monitoring may conceptually
95 be most strongly linked to ground-based approaches, this does not mean rejecting technology.
96 Rather, it means ensuring that IPLCs lead the choice of monitoring approach and are equipped
97 to manage both ground-based and tech-based methods where appropriate.

98 In recent years, the focus on monitoring tree cover change – largely tracking carbon-
99 sequestration goals set by Global North actors (Fleischman et al. 2020) – has in part driven a
100 shift toward tech-based approaches for assessing large-scale conservation and restoration
101 commitments (Ford et al. 2024). We use 'tech-based' broadly to encompass satellite remote
102 sensing, drone-based LiDAR, eDNA metabarcoding, ecoacoustics, and related sensor-driven
103 methods. Tech-based monitoring is well suited for measuring changes in tree cover and carbon
104 accumulation, two metrics that dominate conservation and restoration policy discourses (Lewis
105 et al. 2019). For example, the Tropical Forest Forever Facility, a Brazil-led initiative linking
106 results-based payments to satellite-monitored forest cover, relies on remote sensing to assess
107 performance across up to 74 participating countries .

108 Emerging nature-finance instruments promote monitoring, reporting, and verification
109 (MRV) that prioritizes scalability over ecological insight (TFFF Steering Committee 2025, World
110 Economic Forum 2025, Zu Ermgassen et al. 2025), and MRV-focused 'nature tech' firms
111 capture a disproportionate share of conservation technology funding (Wunder et al. 2025).
112 Disclosure frameworks such as the Taskforce on Nature-related Financial Disclosures (TNFD)

113 increasingly mediate corporate sustainability priorities, shaping both which ecological outcomes
114 are monitored and the methods used, particularly where corporate actors dominate nature
115 finance (TNFD 2023, World Economic Forum 2025). Consequently, conservation and
116 restoration monitoring commonly reflects the interests of external institutions rather than local
117 stewards, producing a system optimized for marketability and scale, instead of ecological insight
118 and equity. To test whether the choice of monitoring is shaped by funding structure, we
119 conducted a new analysis of data from a global sample of intermediary reforestation
120 organizations (Schubert et al. 2026); finding that market-based organizations cite remote
121 sensing far more often than mission-based ones, a gap that has widened over the past two
122 decades (Box 1).

123 The concern is not that technology is replacing ground-based monitoring outright – most
124 organizations layer remote sensing on top of site visits – but that analytical capacity, data
125 ownership, and the potential economic benefits of monitoring increasingly flow away from
126 IPLCs. At the same time, the growing emphasis on tech-based monitoring risks sidelining
127 ecological information that only ground-based approaches can capture – for example, when a
128 project commissions an external firm to conduct tech-based monitoring instead of training and
129 paying a local field team to collect the same data. The broader shift in ecology toward statistical
130 and model-driven approaches has come at the expense of observational, locally grounded
131 studies (McCallen et al. 2019, Anderson et al. 2021), reinforcing the perception that tech-based
132 approaches are the standard for rigorous monitoring (Fig. 1a).

133 Tech-based monitoring is also widely assumed to be less expensive, yet this has rarely
134 been tested and does not always hold when it has. In many tropical contexts, ground-based
135 approaches can be cost-competitive with, or cheaper than, tech-based alternatives, particularly
136 where the analytical infrastructure for processing remote-sensing data is absent (Table 1). For
137 example, a 130-ha commercial LiDAR survey in Indonesia was quoted to us at ~US\$12,100,
138 enough to cover a year of wages for up to a five-person local field team, yet delivers only point-
139 cloud and elevation data, not biomass estimates. In a Panamanian project involving members of
140 the author team, monitoring bird diversity with acoustic recorders cost ~20% more than expert
141 point counts, driven by imported hardware and specialized analysis (Tables S1, S2).

142 Here, we argue that technology should support, not sideline, ground-based, locally led
143 monitoring. Building on calls to integrate local and tech-based monitoring (Danielsen et al. 2021,
144 Tabor et al. 2025) and frameworks for why and when monitoring is justified (Helmstedt et al.
145 2025), we ask: how are monitoring methods shaped by funding structures, and who stands to
146 benefit? Drawing on empirical evidence (Box 1), we describe these dynamics and diagnose how

147 research, policy, and market incentives interact to produce self-reinforcing monitoring lock-in
 148 (Figure 1a). We then offer actionable recommendations for three stakeholder groups –
 149 researchers & research institutions, policymakers, and project developers & standards bodies
 150 (those that design, carry out, and certify monitoring) – to reinvest in ground-based monitoring
 151 and better integrate tech-based and traditional tools (Figure 1).

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155 **Table 1.** Cost comparison of tech-based and ground-based monitoring approaches in two
 156 tropical settings. Costs reflect total project expenditure for each method, including personnel,
 157 equipment, and data collection. See Tables S1 and S2 for full cost breakdowns. All costs in
 158 2025 USD (see Tables S1 and S2 for conversions). *Excludes survey-crew travel,
 159 accommodation, and per diem.

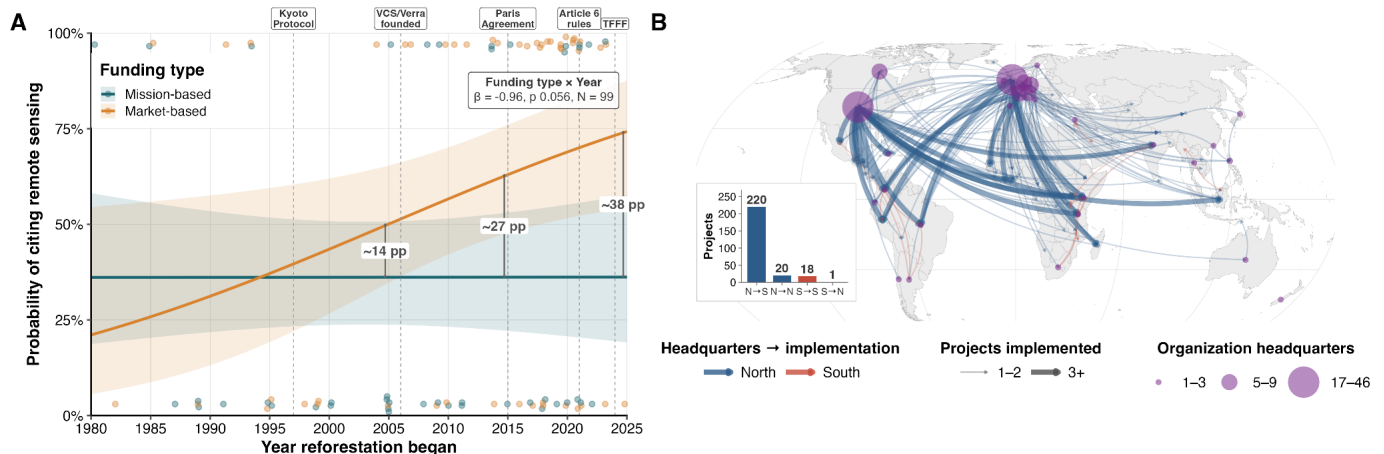
Monitoring goal	Location and scale	Tech-based method	Tech cost (USD)	Ground-based method	Field cost (USD)	Key finding
Vegetation biomass	Indonesia (130 ha)	Aerial LiDAR scan	\$12,100*	Tree inventory (Trained local field technicians)	\$200-\$910 per month per technician	One 130-ha survey ~ up to a 5-person field team for a year (13-60 technician-months across wage ranges)
Bird diversity	Panama (64 sites)	Autonomous recording units (64 AudioMoths, 1 year)	\$105,028	Point counts (local field technician + PhD student; 2 seasons)	\$87,588	Acoustic monitoring cost ~20% more; mostly equipment and data storage, plus a more costly processing phase

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Box 1. Market incentives shape how reforestation is monitored

Using survey data from 130 intermediary reforestation organizations (Schubert et al. in review), we asked whether the choice of monitoring is shaped by funding structure, a question not addressed in the original study. We find that remote-sensing adoption among market-based organizations has risen over time, strengthening its link to funding structure. Organizations with market-based funding (e.g., corporate sponsorship, carbon credit revenue) cite remote sensing as part of their verification approach more often than mission-based organizations (grants, government, endowments): 56% vs. 38% (N = 100). Market-based organizations showed a significant increase in remote-sensing adoption over time, whereas no significant trend emerged across the sector as a whole. This gap grew from roughly 14 percentage points in 2005, when voluntary carbon markets began to scale, to approximately 38 points by 2025 (panel A).

Half of market-based organizations combine remote sensing with site visits, compared with less than a third of mission-based organizations – in both groups, fewer than 2% use remote sensing as a standalone method. The organizations driving this trend are overwhelmingly headquartered in the Global North (high-income economies per the World Bank classification) while implementation concentrates in the Global South (low- and middle-income economies), particularly East Africa and Latin America (panel B). Thus, the concern is less about direct monitoring method substitution than about where analytical capacity and economic benefits ultimately reside. As one organization noted: "We use a combination of ground-level monitoring, drone technology, and satellite imagery to track and verify the location and health of the trees we plant, relaying that information to our partners through their own unique dashboards..." These data are primarily self-reported, and the funding categorization reflects each organization's primary source, but they offer an important window into what influences the choice of monitoring in these projects.



A) Predicted probability of citing remote sensing by year reforestation began and funding type (logistic regression, N = 99). Market-based organizations show a significant increase over time (odds ratio = 2.62, 95% CI [1.14, 6.00], p = 0.023); the interaction with mission-based funding is marginal (odds ratio = 0.38, 95% CI [0.14, 1.02], p = 0.056), but a year-only model shows no significant trend (odds ratio = 1.39, p = 0.114), indicating that the gap is funding-type specific. Dashed lines mark policy milestones; shading shows 95% CIs. **B)** Headquarters-to-implementation connections, colored by the region of the headquarters: Global North (blue) or Global South (red). Line weight is proportional to the number of projects implemented in each destination country (thin: 1–2 projects; thick: 3+ projects). Purple circles denote headquarters locations, sized by the number of organizations headquartered in each country. **Inset:** total organization-implementation pairs grouped by headquarters region → implementation region. North → South flows (n = 220) dominate the other three categories by roughly an order of magnitude; South → North flows are effectively absent (n = 1, a Lebanese organization implementing in Saudi Arabia). Global North/South follow the World Bank high-income classification. In our analysis of data from Schubert et al. (2026), 70 organizations (54%) contributed direct survey responses, the remainder were characterized from public information. Logistic regression fitted with glmTMB (binomial family, logit link). See *Supplementary Materials* for full methods.

168 **The current monitoring imbalance and its consequences**

169 Remote sensing and ground-based monitoring capture fundamentally different
170 information. For instance, satellite-based deforestation alerts can provide near-real-time
171 detection across inaccessible terrain that ground-based methods cannot match at large scale
172 (Hansen et al. 2013). Yet remote monitoring still struggles to capture biodiversity and ecological
173 processes below the canopy, a limitation that persists despite technological advances (Pettorelli
174 et al. 2014). While satellite-derived indicators are improving, they cannot capture processes
175 critical to restoration such as the recovery of seed-dispersing animal populations or shifts in
176 species composition through successional stages (Bello et al. 2015, 2024). Nor can remote
177 sensing detect selective harvesting, hunting of seed-dispersing animals, or livestock
178 encroachment, changes that only ground-based monitoring can reliably detect (Fagan et al.
179 2026). Other emerging tech-based monitoring approaches also face important limitations. For
180 example, eDNA methods can detect species presence but generally cannot provide reliable
181 abundance estimates (Beng and Corlett 2020), and detections depend on species-specific DNA
182 shedding rates and environmental persistence (Andruszkiewicz Allan et al. 2021). Acoustic
183 monitoring is limited to vocalizing species and may miss silent or infrequently calling taxa
184 (Bradfer-Lawrence et al. 2019). Both also depend on reference libraries (of genetic sequences
185 and species vocalizations) that remain incomplete, constraining taxonomic resolution and
186 detection accuracy (Bradfer-Lawrence et al. 2025).

187 A common framing positions ground-based methods as unreliable, promoting technology
188 as corrective rather than complementary (Shen et al. 2024), but these characterizations warrant
189 scrutiny. Participatory approaches have demonstrated accuracy comparable to or exceeding
190 remote sensing in some applications (Iheaturu et al. 2025). Monitoring systems that combine
191 standardized protocols with the contextual knowledge of local observers can produce more
192 equitable and actionable datasets (Kühl et al. 2020). In Panama's Darién, an Indigenous-led
193 project trained 24 technicians who measured 30 one-hectare plots; error analyses and
194 comparisons against Barro Colorado Island simulations confirmed their participatory protocol
195 accurately captured plot-level aboveground biomass (Mateo-Vega et al. 2017). For many
196 ecological metrics, ground-based methods outperform tech-based alternatives: field plots and
197 transects yield more accurate data for fine-grained indicators such as seedling recruitment
198 (Gong et al. 2024, Wang et al. 2024, Fleischman et al. 2025), though the relative performance
199 of field and eDNA methods remains context-dependent (Borràs Sayas et al. 2025).

200 At landscape scales, ground-truth data remain essential for calibrating satellite-derived
201 estimates (Celebrezze et al. 2024), particularly in restoration contexts where young, structurally

202 heterogeneous stands confound allometric models calibrated on mature forests (Xu et al. 2024,
203 Leoni et al. 2025). Data fusion frameworks that integrate field observations with remote sensing
204 have demonstrated this complementarity in practice: in Nepal's Chitwan District, community-
205 collected plot data calibrated satellite-derived canopy models with high accuracy (Murthy et al.
206 2017), and the GEO-TREES network (<https://www.geo-trees.org/>) coordinates permanent field
207 plots specifically designed as foundational inputs to satellite biomass products. Despite this
208 evidence, current verification standards and nature-finance instruments typically accept satellite-
209 derived metrics but lack frameworks for incorporating community-collected data. Investor and
210 funder preference for standardized, scalable metrics reinforces reliance on approaches that can
211 be applied uniformly across geographies, regardless of whether they capture the outcomes that
212 matter most on the ground. In this way, the choice of verification method becomes a
213 governance decision – determining not only what is measured, but also but who participates in
214 and benefits from the monitoring process.

215 This governance imbalance often operates through a capacity gap. Tech-based
216 approaches such as acoustic monitoring and drone-based LiDAR can produce large volumes of
217 data in short periods, but resource-limited projects often lack the expertise to translate these
218 data into ecological insights (Hahn et al. 2022). This expertise gap reflects a broader limitation:
219 tech-based monitoring often centralizes data processing with external specialists, frequently
220 based in the Global North or urban centers in Global South countries, rather than building local
221 capacity (Urzedo et al. 2025). The growing use of artificial intelligence to process satellite,
222 acoustic, and image data (Tuia et al. 2022), can deepen this dependence, concentrating
223 analytical control in the institutions that build and run the models rather than in the communities
224 whose landscapes they describe (Wearn et al. 2019). In practice, this expertise gap often
225 results in data that cannot be used by people on the ground. A single drone flight or camera-trap
226 rotation can produce gigabytes of data, but translating that volume into ecological insight
227 requires computational resources and analytical expertise that many implementing
228 organizations do not have in-house (Tabor et al. 2025). As a result, IPLCs are often confined to
229 short-term data collection roles rather than leading analysis, forgoing livelihood benefits and
230 withholding the place-based knowledge that makes monitoring data interpretable in the first
231 place (Figure 2).

232 The shift toward tech-based monitoring risks transferring data collection and ownership
233 away from local teams, marginalizing place-based ecological knowledge, and eroding
234 employment pathways through which restoration sustains local economies (Danielsen et al.
235 2021, Hernandez-Montilla et al. 2026). Local employment in stewardship and monitoring can

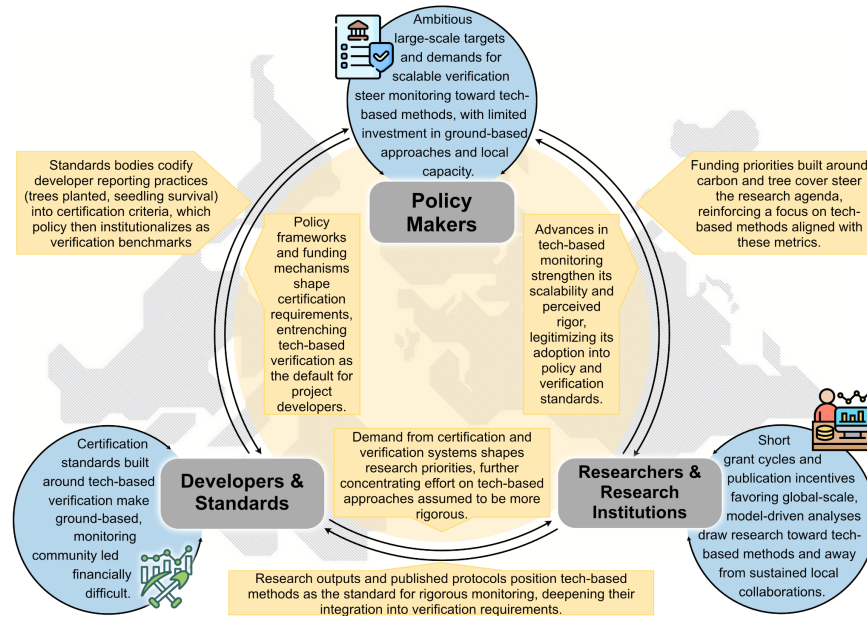
236 provide long-term benefits beyond landowner payments – through wages, skill development,
237 and sustained engagement with restored landscapes (Thomas et al. 2024). Yet growing
238 pressure to scale monitoring has concentrated authority over what is measured and who
239 controls data in Global North institutions (Faxon and Chapman 2025). Even programs designed
240 around community participation can be undermined: in the Khasi Hills REDD+ Project in India,
241 Indigenous communities manage their forests, but externally defined carbon accounting
242 requirements constrain their ability to set monitoring priorities (Poffenberger 2015). Moreover,
243 REDD+ programs have in some cases skewed landscapes toward maximum carbon
244 accumulation to meet Global North targets, sidelining interventions better suited to local
245 contexts (Hajjar et al. 2021, Redvers et al. 2025). Excluding IPLCs from these processes means
246 crucial place-based knowledge is excluded (Mbizah et al. 2026), which increases the risk of
247 project failure (Mazón et al. 2021). Conversely, when IPLCs lead restoration design and are the
248 main beneficiaries, restored areas are protected and monitored more reliably (Sattayapanich et
249 al. 2022), echoing Ostrom's (1990) argument that communities sustain shared resources most
250 effectively when those who depend on them help set the rules and monitor compliance. The risk
251 is structural: when interpreting monitoring data requires specialized capacity, the outside
252 institutions tasked with doing so decide what counts as project success, and therefore what is
253 funded and sustained.

254 Importantly, tech-based monitoring cannot measure social outcomes, making the
255 absence of ground-based monitoring particularly problematic for evaluating whether
256 conservation and restoration deliver equitable benefits (Holl et al. 2022). The community
257 benefits most frequently cited by reforestation organizations – income, education and training,
258 wellness, and food security (Schubert et al. 2024) – all require direct engagement with local
259 people for assessment, including attention to intra-community power imbalances that shape
260 how costs and benefits are perceived and distributed. While 98% of intermediary organizations
261 publicly describe the benefits IPLCs would receive from tree-growing projects, only 38%
262 reported outcomes of these metrics (Schubert et al. 2024).

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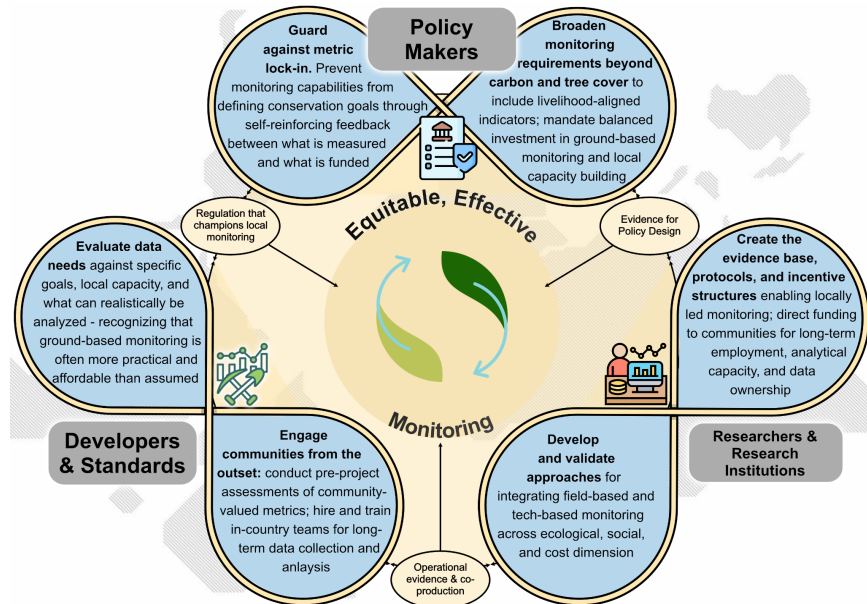
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Figure 1. Market-driven funding and policy incentives risk creating an imbalanced monitoring cycle; reorienting toward equity requires interdependent action across researchers & research institutions, policymakers, and project developers & standards bodies. (a) The current cycle: market-driven funding structures and narrow verification requirements create a self-reinforcing loop that favors tech-based monitoring over locally led approaches. (b) A virtuous cycle converging on equitable, effective monitoring: technology supports rather than crowds out locally led monitoring, with the three stakeholder groups connected by interdependent pathways in which each group's actions strengthen the others. The three groups correspond to the recommendation sections of the manuscript.

284

285 **Recommendations for researchers & research institutions**

286 Ground-based and tech-based methods capture complementary information, and
287 integration frameworks have demonstrated their combined value. Realizing this potential at
288 scale requires institutional change within the research community. A recent push for
289 researchers and IPLCs to co-produce knowledge through stronger collaborations has led to
290 novel frameworks that aim to advance understanding of biological phenomena alongside
291 addressing societal challenges, such as lack of local employment and capacity in monitoring
292 (Evans et al. 2018, Longdon et al. 2024). Yet despite growing mandates for community
293 engagement in conservation and restoration funding, the ephemeral nature of research grants –
294 typically three to five years – often limits participation to short-term project cycles that are far too
295 brief to properly understand the socio-ecological context of a project or to build lasting local
296 capacity (Erbaugh et al. 2020). Publication incentives can compound the problem: high-impact
297 journals have in recent years placed a strong focus on global-scale analyses of conservation
298 and restoration opportunity (e.g., Bastin et al. 2019, Brancalion et al. 2019, Strassburg et al.
299 2020, Mo et al. 2023), and scientific evaluation criteria rarely reward the sustained, place-based
300 collaborations that community-led monitoring requires.

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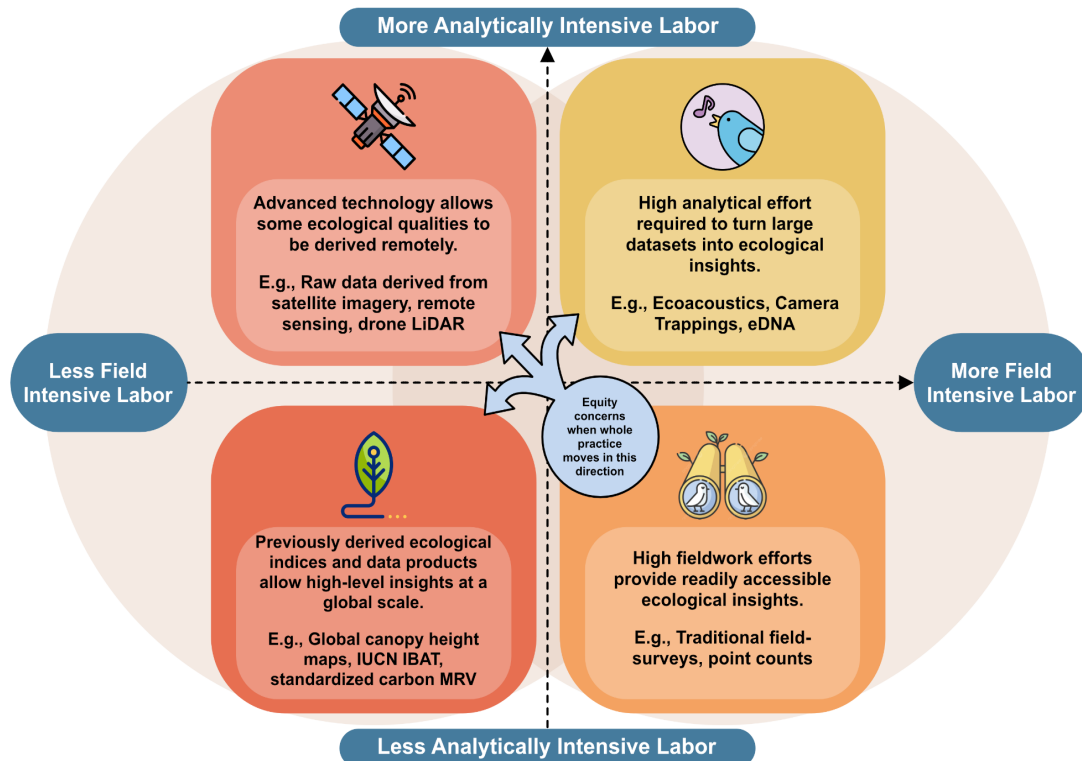
302 **Recommendation 1: Build local leadership into research structures.** To enable locally led
303 monitoring, the research community should advocate for institutional changes: grant
304 requirements that mandate and budget for community engagement in research; standardized
305 yet adaptable monitoring protocols designed for long-term practitioner use (Lindenmayer and
306 Likens 2010); and reformed authorship and recognition practices that give local collaborators
307 equitable credit (Cooke et al. 2021). Equally important is ensuring that communities retain
308 control over the data collected in their landscapes. Budgets also rarely cover the long-term data
309 storage and management that locally held monitoring requires, so dataset ownership tends to
310 migrate to better-resourced external partners. Training for local collaborators in data
311 visualization and analysis is rarely included in research budgets (Danielsen et al. 2021, Reyes-
312 García et al. 2022), and even when federal funding agencies support local collaboration in
313 principle, institutional payment mechanisms and reporting requirements often make it difficult to
314 direct resources to field collaborators in low-income countries. Closing these gaps requires
315 funders and institutions to budget explicitly for long-term data storage, local analytical training,
316 and authorship-based recognition, and to adopt payment mechanisms that can more easily
317 direct resources to field collaborators in low-income countries.

318 Clear data governance agreements should be established at the outset of any project
319 (Thung et al. 2026), and more fundamentally, wherever possible, IPLC members should help
320 shape the research questions and choice of methods from the outset; a process that brings
321 local actors in only after the agenda is set is unlikely to be either just or effective. Long-standing
322 participatory programs illustrate what is possible: the parataxonomist model in Costa Rica's
323 Área de Conservación Guanacaste has trained and employed hundreds of local people in
324 monitoring over several decades, generating high-quality datasets while providing stable
325 employment (Janzen and Hallwachs 2020). Yet when monitoring technologies generate data
326 that hold no practical meaning for IPLCs, they risk displacing local approaches. Acoustic
327 recorders, for instance, generate vast datasets, but the analytical tools to extract ecological
328 meaning remain inaccessible without specialized training (Gibb et al. 2019). Investing in local
329 analytical capacity can improve data quality through contextual interpretation while ensuring that
330 monitoring generates sustained employment within conservation and restoration landscapes.

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332 **Recommendation 2: Develop the evidence base for how to effectively integrate tech- and**
333 **ground-based methods.** We encourage researchers & research institutions to develop the
334 evidence base for integrating tech-based and traditional ground-based approaches. This
335 includes comparative studies of how different monitoring frameworks perform across ecological,
336 social, and financial dimensions. Such work can build on emerging evidence that field-based
337 methods match or outperform tech-based approaches for many ecological metrics (Danielsen et
338 al. 2021, Gong et al. 2024, Iheaturu et al. 2025). A key barrier to broader adoption of ground-
339 based methods is the perception that they lack consistency across sites; standardizing *in situ*
340 monitoring protocols and public data sharing platforms could help address this limitation.

341 By developing data fusion frameworks that integrate field observations with remote
342 sensing and other sensor platforms, more comprehensive assessments of conservation and
343 restoration progress can be implemented while maintaining local involvement (Wang et al. 2024,
344 Iheaturu et al. 2025). Key examples illustrate this integration in practice. In Ethiopia's Kafa
345 Biosphere Reserve, local forest rangers submitted georeferenced disturbance reports via
346 smartphones, which were used directly as training labels for a Landsat-based random forest
347 classifier to detect forest degradation (DeVries et al. 2016); also see Nepal and GEO-TREES
348 examples above).

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 351 **Figure 2.** Conservation and restoration monitoring methods positioned along two axes: field
 352 labor intensity (horizontal) and analytical labor intensity (vertical). Shifts away from traditional
 353 field surveys (*bottom right*) in any direction can raise equity concerns: toward satellite remote
 354 sensing (*top left*), local field presence is reduced; toward ecoacoustics and camera trapping (*top*
 355 *right*), analytical complexity can exclude local participants; toward pre-built indices (*bottom left*),
 356 engagement with ground-level processes is abstracted away. In each case, local employment,
 357 data ownership, and participation in monitoring can be diminished if not approached in an
 358 equitable manner.
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360 **Recommendations for policymakers**

361 Market-driven adoption of remote sensing, carbon-centric verification requirements, and
 362 the centralization of analytical capacity are all reinforced by policy frameworks that have
 363 traditionally underinvested in monitoring (Fagan et al. 2020), and have set ambitious targets
 364 (e.g., the Bonn Challenge, <https://www.bonnchallenge.org/>; Trillion Trees, <https://trilliontrees.org/>)
 365 without clearly specifying how ecological outcomes will be tracked on the ground or how
 366 monitoring design will support IPLCs. Current policy proposals continue this trend, creating
 367 funding mechanisms that rely primarily on remote sensing without adequately weighing the
 368 tradeoffs between remotely sensed metrics and the ecological and social outcomes they omit
 369 (e.g., Corson and Campbell 2023)

370 Without clear monitoring requirements, policy frameworks risk undermining both the
 371 ecological effectiveness and social equity of programs and, by leaving an incomplete picture of

372 their benefits and costs, limiting the evidence needed to improve future policy. For example,
373 grant guidelines for Australia's '20 Million Trees' program specified that no more than 5% of
374 funds could be spent on monitoring (Commonwealth of Australia 2016), contributing to short-
375 lived projects (Schubert et al. 2024, West et al. 2025) and social justice risks (Parris-Piper et al.
376 2023). More broadly, funding is often channeled indirectly and non-transparently (Tabor et al.
377 2025), creating financial uncertainties for IPLCs that reduce participation incentives and limit the
378 potential for monitoring to provide sustained employment (ILO-UNEP-IUCN 2024). Integrated
379 monitoring and early community involvement in policy design could help prevent these
380 outcomes (Evans et al. 2018, Höhl et al. 2020), but it requires that policy frameworks set
381 tangible ecological targets beyond hectares restored and ensure that monitoring design
382 supports local employment and capacity.

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384 **Recommendation 1: Measure the outcomes communities value and ensure community-**
385 **engaged monitoring is required.** We encourage policymakers to focus on a range of
386 landscape restoration outcomes and recognize that prioritizing some (such as carbon
387 drawdown) over others (such as those aligned with local livelihood objectives) risks driving
388 social inequalities and jeopardizing ecological outcomes (Löfqvist et al. 2023b). This includes
389 outcomes that often matter most to IPLCs – such as water quality and availability, access to
390 agricultural and non-timber forest products, income, and livelihood diversification – outcomes
391 that are rarely captured by remote sensing but are central to whether conservation and
392 restoration are perceived to deliver equitable benefits (Danielsen et al. 2021). In the absence of
393 certification requirements for community-engaged monitoring, project developers who invest in
394 participatory approaches risk financial penalties relative to competitors that depend solely on
395 tech-based systems (Schubert et al. 2026) – a dynamic we address further in our
396 recommendations for project developers & standards bodies below. Regulatory frameworks
397 must therefore establish a floor for community-engaged monitoring to prevent this race to the
398 bottom. Nearly half of tree-growing organizations publicly report the percentage of funding
399 reaching local projects, yet these rarely acknowledge the true costs of rigorous, long-term
400 monitoring (Schubert et al. 2024). Policymakers can actively address this by promoting
401 standards with more stringent criteria for required monitoring, especially for projects that
402 generate offsets sold to Global North countries or private actors, where the benefits accrue far
403 from the landscapes bearing the monitoring burden. Importantly, more stringent monitoring
404 requirements need to be coupled with increased public funding and support for local project
405 developers, otherwise there is a risk that more sophisticated monitoring requirements bias

406 nature finance towards socio-economically stronger landscapes and/or projects led by actors
407 with stronger financial means.

408 Currently, non-remotely-sensed metrics are often bureaucratic counts, such as the
409 number of companies filing nature-related financial disclosures under the Global Biodiversity
410 Framework or the number of trees planted (Schubert et al. 2024), that are easy to collect but tell
411 little about actual ecological outcomes or impact on communities. We argue that a minimum
412 percentage of conservation and restoration program budgets should be allocated to traditional
413 ground-based monitoring and local capacity building, a requirement largely absent from current
414 policy frameworks (Evans et al. 2018). Precedents exist for embedding ground-based ecological
415 assessment within policy design. Ireland's Burren Program (2010-2022) conditioned agri-
416 environment payments on annual field assessments by trained advisors who scored habitat
417 quality on each farm, demonstrating that results-based payment schemes can maintain
418 ecological monitoring capacity at scale when supported by sustained investment in training and
419 coordination (Moran et al. 2021). Similarly, the Global Biodiversity Standard's regional hubs
420 train local assessors to conduct ground-based verification, building in-country monitoring
421 capacity rather than relying on external auditors (Bartholomew et al. 2026). Commodity
422 certifications can also engage communities in biodiversity monitoring. For example, the Bird
423 Friendly coffee certification trains coffee farmers and cooperatives to assess the biodiversity
424 value of their farmland by conducting simple habitat surveys (e.g., canopy cover, binned tree
425 species richness) that broadly correlate with the overall richness and diversity of birds (Bennett
426 et al. 2022).

427
428 **Recommendation 2: Avoid letting what is straightforward to measure remotely define**
429 **overall goals.** When monitoring capabilities define project goals, rather than the reverse, a self-
430 reinforcing cycle often emerges; metrics that are easy to measure remotely attract funding,
431 which entrenches those same metrics, crowding out outcomes that require ground-based
432 assessment (Hernandez-Montilla et al. 2026). We caution policymakers against allowing this
433 feedback loop to narrow the scope of what restoration is expected to achieve. The risks of
434 metric lock-in are not hypothetical. An assessment of 26 REDD+ carbon projects across six
435 countries found systematic overcrediting, while on-the-ground biodiversity and livelihood
436 outcomes often went unmonitored (West et al. 2023). Emerging reform proposals reflect
437 growing recognition of these limitations. Balmford et al. (2023) propose the PACT framework
438 (Permanent Additional Carbon Tonne) for dynamically valuing impermanent nature-based
439 carbon credits, and Swinfield et al. (2024) argue that refinements in standard, such as realizing

440 credits ex-post project implementation, can increase the chance that credits represent real
441 biodiversity uplift.

442 Despite these emerging reforms, the dominant carbon-centric metrics risk becoming
443 further entrenched as they are institutionalized through mechanisms such as Article 6
444 articulated under the Paris Agreement of UNFCCC (2015), Target 19 in the Kunming-Montreal
445 Global Biodiversity Framework UN CBD (2022), and emerging nature-finance frameworks (*e.g.*,
446 the TFFF; TFFF Steering Committee 2025). These initiatives risk shaping research priorities
447 and future policy at the cost of ecological and social outcomes. Some frameworks have begun
448 to address this pattern. For example, Verra's Sustainable Development Verified Impact
449 Standard (SD VISta) requires projects to report and verify social and biodiversity outcomes
450 alongside carbon (Verra 2024), although uptake remains limited (62 standalone projects as of
451 February 2026). Policy design that integrates complementary monitoring approaches from the
452 outset can help ensure that a narrow set of objectives does not come at the cost of positive
453 social impact and biodiversity outcomes.

454

455 **Recommendations for project developers & standards bodies**

456 Project and certification design is often steered toward technology by the assumption
457 that it is less expensive at scale. Our cost comparisons challenge this as field-based monitoring
458 can be cost-competitive with tech-based alternatives in tropical contexts (Table 1), but project
459 and certification design do not often reflect this reality. An emphasis on cost-effectiveness in
460 monitoring can come at the expense of tailoring monitoring to track meaningful ecological and
461 social change resulting from specific interventions – and of ensuring that the monitoring process
462 itself supports IPLCs. This section addresses both project developers (implementing
463 organizations and intermediary funders who often design and carry out monitoring) and the
464 standards bodies (*e.g.*, Verra, Gold Standard) whose verification requirements shape monitoring
465 practice.

466

467 **Recommendation 1: Match the monitoring method to project goals and to local analytical**

468 **capacity.** In determining the appropriate mix of monitoring approaches, project developers &
469 standards bodies should critically evaluate both what data are needed to track progress toward
470 specific conservation or restoration goals and what local capacity exists to analyze those data.
471 Meeting these needs credibly depends on baseline methods that are standardized yet
472 adaptable to local contexts, and current practice falls short. Established protocols for ground-
473 based ecological monitoring can be tailored locally (*e.g.*, Viani et al. 2020), but most cover only

474 a narrow set of metrics, and standardization across restoration settings remains limited. The
475 same gap undermines carbon verification, where competing baseline methods rely on divergent
476 assumptions and can yield very different deforestation baselines for the same area (West et al.
477 2024). Emerging biodiversity credit markets face similar baseline and monitoring challenges
478 (Aide 2024, Wunder et al. 2025), with corresponding integrity problems (Zu Ermgassen et al.
479 2019).

480 The cost data presented in Table 1 challenge the assumption that tech-based
481 approaches are inherently more efficient: in contexts where analytical infrastructure for
482 processing remote sensing data is absent, ground-based monitoring can be both cheaper and
483 more actionable, and the costs of deploying and analyzing data from acoustic recorders can
484 actually exceed those of traditional ground-based methods (Tables S1, S2), despite increasing
485 promotion of automated recorders as scalable and cost-effective solutions to biodiversity
486 monitoring. Beyond cost, accessibility matters. Cloud-dependent data analysis pipelines can be
487 impractical in field settings with limited connectivity, creating unnecessary barriers to local data
488 interpretation and ownership. Where possible, projects should invest in analytical tools and
489 workflows that function offline, with intuitive interfaces, and can be maintained locally. We
490 recognize that public institutions, especially in the Global North, play an important role in helping
491 local project developers meet these goals through funding, technical assistance, and capacity
492 building.

493

494 **Recommendation 2: Co-design monitoring early and build local capacity to keep data**
495 **and its benefits local.** To increase the chance that monitoring generates long-term livelihood
496 benefits, monitoring design should begin before project design is finalized. Pre-project
497 assessments that map existing local monitoring practices and identify community-valued metrics
498 can allow project developers to design monitoring that serves both accountability requirements
499 and community needs, reducing the risk that communities face funding loss for failing to meet
500 standards they had no role in defining. We encourage project developers, and the certification
501 agencies whose requirements shape their options, to partner with local institutions and allocate
502 resources to build local capacity for data collection, processing, and interpretation – including
503 investing in local infrastructure for sample processing and analysis (*e.g.*, in-country lab capacity
504 for eDNA; Shen et al. 2024). As established above, trained community data-collectors can
505 produce estimates comparable to those of conventionally trained scientists, at substantially
506 lower cost (Danielsen et al. 2021). By keeping data interpretation local rather than exporting it
507 for external processing, project developers can reduce dependencies on outside institutions

508 while ensuring that monitoring knowledge remains accessible to those most affected by
509 conservation or restoration outcomes.

510 Yet even project developers with strong capacity to execute ground-based monitoring
511 often cannot financially justify doing so when certification standards and funders require tech-
512 based approaches. If a nature-based credit buyer only requires remote sensing monitoring, a
513 project developer who invests in more comprehensive ground-based methods risks being
514 undercut by competitors who do not, creating a 'race to the bottom' that compromises
515 ecosystem health and social justice (Löfqvist et al. 2023a). One practical step is to allocate a
516 fixed portion of monitoring budgets to sustained local ground-truth data collection, which serves
517 both as an independent check on remotely sensed estimates and as calibration data for local
518 spatial models. Equitable implementation requires transparency at every stage, from who sets
519 the monitoring agenda to how the data are shared (Sandbrook et al. 2021).

520

521 **Conclusion**

522 Current technologies widely promoted for landscape-scale conservation and restoration
523 assessment may inadvertently undermine the local engagement essential for long-term project
524 success and give an incomplete view of progress toward environmental goals. The current
525 trajectory, toward tech-based monitoring shaped by funder- and market-driven requirements,
526 risks sidelining communities from both data generation and the long-term social and economic
527 benefits of conservation and restoration. It also risks reinforcing the impression that tech-based
528 metrics alone can fully capture ecological recovery, when many dimensions of recovery require
529 direct, locally led assessment. Monitoring that integrates technological and ground-based
530 approaches while supporting local capacity building is not only more equitable; it is associated
531 with greater project success and permanence. Researchers & research institutions,
532 policymakers, and project developers & standards bodies each have distinct roles in reorienting
533 monitoring systems toward equity and effectiveness (Figure 1b), and these roles are deeply
534 interdependent; progress requires change in tandem. Ultimately, the choice of monitoring
535 approach is not solely technical; it determines who benefits from conservation and restoration,
536 and whether interventions are effective and equitable at scale.

537

538 **CRedit Authorship statement**

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1 **Supplementary Material for Werden et al. 2026 - Technology should support, not sideline,**
2 *locally driven conservation and restoration monitoring*

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6 **Supplementary Methods - Analysis of monitoring methods across reforestation**
7 **organizations (Box 1 figure).**

8 The data reported in Box 1 are from a global survey of intermediary reforestation
9 organizations conducted by Schubert et al. (2026), in which organizations reported their funding
10 structures, monitoring and verification approaches, geographic location, and area of operation.
11 The analyses reported in Box 1 and the main text are our own and are not presented in the
12 original publication.

13 We classified each organization's primary funding structure as market-based (corporate
14 sponsorship, carbon-credit revenue, or other earned revenue) or mission-based (grants,
15 government funding, or endowments), and recorded whether its self-reported verification
16 approach referenced remote sensing (satellite or drone imagery), alone or combined with
17 ground-based site visits. Of 130 organizations surveyed, 100 reported a classifiable primary
18 funding structure (52 market-based, 48 mission-based); across these, market-based
19 organizations referenced remote sensing more often than mission-based organizations (55.8%
20 [29/52] vs. 37.5% [18/48], respectively).

21 To test whether this association has changed over time, we modeled remote-sensing
22 use as a function of funding structure, the year reforestation began (z-standardized), and their
23 interaction, using logistic regression (*glmmTMB* package; binomial family, logit link; N = 99,
24 restricted to organizations with a known start year). Remote-sensing adoption increased over
25 time among market-based organizations (odds ratio per standard deviation of start year = 2.62,
26 95% CI [1.14, 6.00], p = 0.023), whereas funding types did not differ at the mean start year
27 (main effect of funding structure, p = 0.15) and a year-only model showed no significant sector-
28 wide trend (OR = 1.39, p = 0.114). Together these indicate that rising remote-sensing adoption
29 is specific to market-based organizations. The predicted market- versus mission-based gap
30 widened from ~14 pp in 2005 (50% vs. 36%) to ~38 pp in 2025 (74% vs. 36%; Box 1, panel A).

31 We also summarized the combination of remote sensing with field methods (half of
32 market-based vs. fewer than one-third of mission-based organizations combined the two; fewer
33 than 2% of either group used remote sensing alone) and the geographic distribution of
34 organization headquarters versus implementation sites, classified by World Bank income group
35 (Box 1, panel B). All analyses were conducted in R version 4.5.0 (R Development Core Team,
36 2025).

37 These data are primarily self-reported, and each organization's funding categorization
38 reflects its primary source rather than its full funding portfolio; results should be read as
39 indicative of sector-level patterns rather than precise estimates.

45 **Table S1. Cost estimation of generating vegetation biomass values in Indonesia using**
 46 **either LiDAR scans or field labor.** To compare the cost of ground-based approaches against
 47 technological approaches to monitoring in restoration, we use vegetation biomass calculations
 48 in Indonesia as an example. Indonesia is a country that hosts globally significant biodiversity
 49 hotspots and carbon reserves that are under constant pressure from deforestation and forest
 50 degradation. It is consistently identified as a priority region for ecological restoration including
 51 through carbon and biodiversity crediting schemes. This table outlines the information used to
 52 estimate prices of, and people employed in, vegetation data collection for the two methods.
 53 Estimates are based on a 2025 commercial drone LiDAR quotation obtained by the authors
 54 from an Indonesian operator to conduct flights in Indonesia, delivering point-cloud and elevation
 55 data (not biomass; Commercial UAV LiDAR quotation from an Indonesian operator, 2025;
 56 available on request from the authors). All costs reported in 2025 USD unless otherwise noted,
 57 converted at the 2025 average rate (x-rates.com). *Indicates that the number excludes flights,
 58 accommodation, and per diem for the survey crew.
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Activity	Method	Price	Description
Quantifying vegetation biomass (carbon)	Aerial LiDAR	~\$12,100*	Commercial drone LiDAR survey covering ~130 ha in Lampung and Sulawesi (~IDR 199.8 million = ~US\$12,100). Delivers a 3D point cloud, DSM, and DTM; does not include conversion to biomass values, which requires additional processing.
	Field survey	\$200 - \$910 per month	<i>Low estimate:</i> provincial monthly minimum wage of ~IDR 2.2-5.4 million across provinces (~IDR 3,296,000 = US\$200), as a cross-provincial average (ASEAN Briefing, 2025). <i>High estimate:</i> an entry-level technical field salary (~IDR 15,000,000 = US\$910), an upper bound reflecting skilled/technical pay scales (Economic Research Institute, 2025).

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74 **Table S2. Costs of collecting and analyzing data on bird diversity in shade coffee, sun**
75 **coffee, and forest sites in Chiriquí, Panama;** data are from the Smithsonian Bird Friendly
76 coffee program. Data were collected using two different methods: Point Counts (field
77 observation of birds by sight and sound from an experienced local field technician and graduate
78 student) and AudioMoths (Acoustic Recording Units deployed at the same sites where Point
79 Counts were conducted). AudioMoth units (N = 64) were deployed across coffee and forest
80 sites, spanning a ~200 km² core landscape (20 × 10 km), with sparser coverage extending
81 across a ~20 × 70 km area. Data from Point Counts were gathered in 4 replicated 10-minute
82 observation periods in each of 2 seasons (breeding and non-breeding seasons), while acoustic
83 data from AudioMoths were gathered on a duty cycle of 1-minute recording every 10 minutes,
84 24 hours a day, for a full year. Because the acoustic detection radius of AudioMoths varies by
85 species and vegetation, a precise per-unit sampling area cannot be defined; costs are therefore
86 reported per recording unit. Both methods had the same costs for site selection and collection of
87 associated habitat data. All costs reported in 2025 USD.
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Activity	Method	Description	Cost per unit	Unit	No. units	Point Count Cost	Audio Moth Cost
Initial site selection (contacting landowners, obtaining permissions, establishing 64 sampling points)	Both	PhD student. Tuition and stipend	\$3,000	month	2	\$6,000	\$6,000
	Both	Local field assistant salary	\$1,500	month	2	\$3,000	\$3,000
	Both	Local transportation (truck rental and gas)	\$2,000	month	2	\$4,000	\$4,000
	Both	Local housing	\$285	month	2	\$570	\$570
Equipment	Point Counts	Binoculars	\$350	unit	2	\$700	
	AudioMoths	Memory cards: 3 per audiomoth	\$19	unit	192		\$3,648
	AudioMoths	Batteries (lithium AA)	\$0.78	unit	1152		\$899
	AudioMoths	AudioMoths	\$100	unit	64		\$6,400
	AudioMoths	Cases for AudioMoths	\$50	unit	64		\$3,200
	AudioMoths	20 TB storage on computing cluster	\$2,000	unit	1		\$2,000

Data collection: Habitat data in a 30- m radius around each data collection point	Both	PhD student. Tuition and stipend	\$3,000	month	1.5	\$4,500	\$4,500
	Both	Local field assistant salary	\$1,500	month	1.5	\$2,250	\$2,250
	Both	Local transportation (truck rental and gas)	\$2,000	month	1.5	\$3,000	\$3,000
	Both	Local housing	\$285	month	1.5	\$428	\$428
Data collection. Bird Point Counts. (64 points, 4 repetitions per point per season, 2 seasons)	Point Counts	PhD student. Tuition and stipend	\$3,000	month	4	\$12,000	
	Point Counts	Local field assistant salary	\$1,500	month	4	\$6,000	
	Point Counts	Local transportation (truck rental and gas)	\$2,000	month	4	\$8,000	
	Point Counts	Local housing	\$285	month	4	\$1,140	
Data collection. AudioMoths (64 points; battery and memory card swapped every 60 days)	AudioMoths	Postdoc stipend and travel	\$6,250	month	1		\$6,250
	AudioMoths	Local field assistant salary	\$1,500	month	4.5		\$6,750
	AudioMoths	Local guide for field assistant	\$600	month	3.5		\$2,100
	AudioMoths	Local housing	\$285	month	4.5		\$1,283
Data Analysis	Point Counts	PhD student. Tuition and stipend	\$3,000	month	12	\$36,000	
	AudioMoths	Postdoc stipend	\$5,417	month	9		\$48,750
TOTAL						\$87,588	\$105,028

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