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Paradigms and Principles for Integrating Nature Technology Data: Challenges, Opportunities, and Next Steps in Real-World Biodiversity Monitoring

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ABSTRACT

Employing a combination of nature technology data (NTD) from satellites, eDNA, camera traps, acoustic monitors, and GPS can augment traditional biodiversity measurements to help understand conservation status and outcomes. While previous works have integrated these data, there remains a significant gap between individual exploratory cases and replicable, scalable, and standardized approaches. Notably, there is no clear guidance or consensus on how NTD are best integrated in practice. To address this gap, we propose a set of paradigms (survey design, tip and cue, validation, consilience, interpolation and extrapolation, and data fusion) and prioritize a set of principles (metadata standards, use rights and licensing, scientific rigor, and utility) as the foundations of an actionable framework for NTD integration. We then analyze seven diverse, real-world case studies across biomes, use cases, and user types to understand what paradigms are leveraged in practice, how prioritized principles have been implemented, and identify challenges, opportunities, and next steps. Distilling NTD integration into paradigms helped map the relationships between workflows, such as how low-barrier-to-entry methods (like consilience) can lead to deeper integration (extrapolation or data fusion), and revealed that there are different purposes and tools needed even when sensor use is similar. The paradigms also helped elucidate key challenges (such as mismatches in scale and lack of data, reference libraries, and methodological guidance) and opportunities (increasing data resolution, systematizing guidance, and producing new repeatable tools). For prioritized principles, metadata standards and vehicles for sharing permissions and use rights could increase impact and reuse. We conclude that next steps, including new training resources, use of high-resolution satellite data, increased multimodal field data collection, use of standardized repositories, and APIs that support integration, are needed to operationalize these paradigms and principles. These steps will provide a foundation for realizing the potential of integrated biodiversity monitoring to help guide conservation action.

1 | Introduction

Sound environmental management and policy decisions require robust, regularly updated ecological information; otherwise, decisions can be made using flawed heuristics, fail to address complex situations, and risk being ineffective and costly. This lack of data-based decision-making is a challenge in conservation, spurring initiatives like Conservation Evidence (Conservation Evidence 2026) and quantitative conservation status assessments (IUCN 2025). The global biodiversity framework (CBD 2022), associated national commitments, corporate reporting (McKenzie et al. 2025; Miller et al. 2025; TNFD 2025; NPI 2025), and biodiversity credits have increased demand for scalable, holistic ecosystem monitoring. Overcoming sparse, fragmented, and infrequently updated biodiversity data remains a priority for global conservation efforts. This has been the subject of national and international observatory networks (Keller et al. 2008; Vanderbilt and Gaiser 2017), proposed global observation systems (Gonzalez et al. 2023), and tools that focus on Essential Biodiversity Variables and other key indicators (Griffith et al. 2024).

Employing a combination of nature technology data—which we abbreviate as "NTD" and define as the data streams from physical sensors (e.g., satellite or acoustic recorders) that are distinct from but subsequently flow into downstream models and platforms—can provide ecological insights for conservation decision-making (Bell and Malerba 2025). However, significant technical and operational challenges remain in deploying sensors, collecting NTD, and synthesizing the results (Marvin et al. 2016; C. B. Anderson 2025). While previous literature has surveyed integrated biodiversity monitoring (Henry et al. 2008), there remains a significant gap in understanding what works in practice for extracting timely insights at scale to inform decision-making. Notably, NTD pose unique challenges for integration not addressed in existing works, and there is not yet broad consensus on how NTD are best integrated in practice, nor how they can be automated for improved scalability (King and Halpern 2025). Our contention is that for many conservation applications, including protected area management, biodiversity credits, applied research, and nature reporting, there is a need for replicable, scalable, timely, and accessible integrated NTD.

In this paper, we identify the foundations of an actionable framework for how NTD can be integrated in practice and enhance understanding of conservation status and interventions across multiple scales. First, we propose a set of paradigms for how NTD can be integrated to produce actionable insights for practitioners. Next, we consider how existing principles for data collection and management apply to the challenges and needs of NTD integration and prioritize several principles based on expert input. We then present a diverse set of real-world case studies to understand which paradigms are actively leveraged in practice and how priority principles have been implemented. Finally, we identify challenges, opportunities, and next steps for harnessing these paradigms for conservation decision-making.

2 | Paradigms for Nature Technology Integration

Multimodal data integration has benefitted medicine (Cai et al. 2019; Xu et al. 2024) and Internet of Things (IoT; Al-Fuqaha et al. 2015). In comparison, the integration of NTD is a nascent but growing effort for biodiversity monitoring (Besson et al. 2022; Hartig et al. 2024; Sutherland et al. 2025), featuring a wide variety of data streams and limited documentation and research on integration techniques, methodologies, and benefits (Lahoz-Monfort and Magrath 2021). Literature on NTD integration is primarily composed of case studies, including combining data from passive acoustic monitoring and camera traps (Buxton et al. 2018; Rich et al. 2019; Growcott et al. 2025) and merging data from satellites and camera traps for occupancy modeling (Niedballa et al. 2015), with sparser examples of other NTD combinations (Rappaport et al. 2022; Dixon et al. 2023; Scarpelli et al. 2023). To help identify challenges, opportunities, and next steps, understand how similar sensors can be used for different purposes, and map relationships between processes, we categorized different integration workflows. Based on relevant literature, a review of reported projects using the NICFI Satellite Data Program, and expert input from conference sessions and virtual convenings of nature technologists (NTC 2025), we identified six paradigms for NTD integration. We define "NTD integration" as using multiple NTD streams in an overall conservation workflow, though the inputs, structure, and outputs of these workflows (ranging from survey design to multi-modal data fusion) can vary significantly under this umbrella term (Figure 1).

2.1 | Survey Design

In survey design, researchers draw on direct or derived data from one sensor to develop their sampling strategy for another type of sensor (Dalton et al. 2024). The purpose is to identify where, when, and sometimes which NTD to sample to detect a target species presence or behavior. The first sensor helps to delineate and limit the spatial and/or temporal use of the other sensor(s). For example, the site sampling strategy for a camera trap survey could be determined based on satellite-derived habitat mapping.

2.2 | Tip and Cue

Tip and cue emerges from the field of satellite remote sensing, where one sensor indicates a possible event of interest, and another satellite, typically with higher spatial resolution, confirms the event (Goana et al. 2024). For conservation, tip and cue entails NTD from one sensor alerting to an ecological change, followed by a different sensor to further characterize or confirm the change or its implications. The purpose is to provide a warning or indicator of a change in time to react to it, often by taking a management or enforcement action. For example, a satellite monitoring large areas of forest detects evidence of tree mortality. Using the "tip" from the satellite data, field teams then "cue" an evaluation of already-deployed in situ passive acoustic sensors to assess whether this

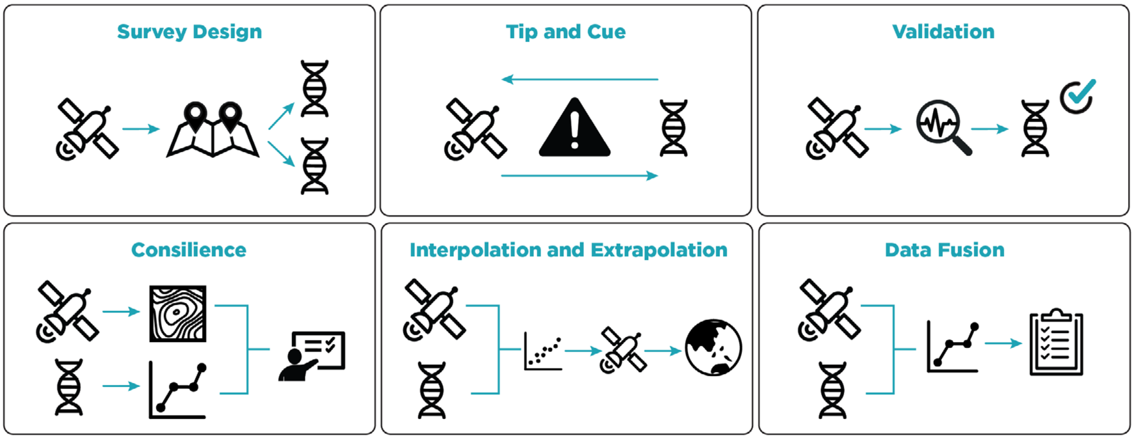

FIGURE 1 | Schematic of paradigms for nature technology data integration.

forest disturbance has affected bird species conservation status and if management actions are required.

2.3 | Validation

Validation occurs when data from one type of NTD is used to verify the findings of another. The first sensor provides a proxy or low-confidence finding, while the second senses more directly the object of interest for a confirmatory result. The purpose is to build confidence in a finding, such as a species detection or ecological change, differentiating it from the paradigm of tip and cue above, which is focused on warnings and indicators for enforcement action. For example, satellite data indicate the presence of wildebeest herbivory, and eDNA or camera traps confirm wildebeest presence. Alternatively, an eDNA sample could indicate the presence of an endangered species, which is verified with camera trap images or acoustic-derived sound identification.

2.4 | Consilience

Consilience is when NTD from multiple sensors are analyzed independently. The outputs are manually compared to derive new conceptual insights, but the data are never directly integrated to produce wholly new metrics. As an example, bioacoustic data are used to produce findings on bird populations and eDNA is used to derive metrics on aquatic fauna independently; the concurrent increasing trends in both species groups are used together to indicate improvement in ecosystem health.

2.5 | Interpolation and Extrapolation

With interpolation and extrapolation, a feature in an extensive dataset correlates with a spatially and/or temporally narrower dataset, and the extensive dataset is leveraged to expand findings from the narrower dataset (C. B. Anderson 2018). This correlation typically uses computational modeling to either fill gaps to create spatially or temporally continuous datasets within the area or time frame where sparse data have been collected (i.e., interpolate) or expand the spatial or temporal extent to new areas or time frames (i.e., extrapolate). The purpose of this paradigm is to expand results beyond the range of a narrow, but high-confidence NTD by correlating with other NTD of broader extent. For example, establishing a relationship between satellite-derived environmental variables and site-derived species occurrence to estimate species distribution in areas without in situ sampling.

2.6 | Data Fusion

Data fusion uses data from two or more sensors, delivered concurrently and synthesized into a new metric that could not be derived from a single sensor, to support decision-making or serve as an input to further analysis (Isaac et al. 2020; Czúcz et al. 2021; Trantas et al. 2025; Yu et al. 2025). A key differentiating factor is that a new data layer is developed and used as a unit, requiring data from multiple sensors to produce and update it. For example, an ecosystem condition index incorporates both ecosystem structure metrics from satellite data (e.g., canopy height) and compositional intactness derived from in situ sensors. This index is then incorporated into scenarios to assess how ecosystem condition might change for corporate sustainability reporting.

Although these paradigms can overlap or be interdependent, they are applied for different conservation purposes and serve to elucidate targeted guidelines and principles for NTD integration.

3 | Principles for an Integrated Nature Data Future

Three sets of complementary principles are commonly used by the academic and nature technology sectors for the process of data collection, management, and reuse: FAIR (Wilkinson et al. 2016), CARE (Carroll et al. 2020), and TRUST (Lin et al. 2020). FAIR focuses on data clarification, retrieval, and reuse; TRUST stresses transparent and sustainable repositories; and CARE promotes equitable participation, openness, and accessibility (O'Brien et al. 2024).

While FAIR, CARE, and TRUST address critical aspects of scientific data management and governance, they do not include all aspects relevant for integrators of diverse, heterogeneous scientific data, such as the quality, reproducibility, and fit-for-purpose design of data, models, software, and scientific workflows (Royaux et al. 2025; Trochim and Roy 2025; Wilkinson et al. 2025). To address this, we reframed well-established practices by convening experts in NTD (first at a conference and then in subsequent virtual convenings) to define principles that are or should be used in practice (henceforth "data integration principles"; Table S1.1). We then cross-referenced these data integration principles against FAIR, CARE, and TRUST to identify gaps and existing principles needing renewed attention for NTD integration.

We found two existing data principles in our analysis (Table S1.1) that hold special relevance for NTD integration: metadata standards for data interoperability and interpretation, and use rights and licensing for data access and reuse during integration (see Table S1.2). Experts suggested metadata standards are important for data transfer and machine-readability, particularly as integrated data are reused, become part of derived datasets, or incorporated into global databases. For example, standard annotation using Darwin Core helps maintain consistency and interoperability across species observation data in the Global Biodiversity Information Facility (GBIF 2025). An understanding of licensing terms is also critical when creating derivative datasets, connecting tools, or reusing integrated data and products; for instance, the use of "copyleft" products in workflows requires all derivative products to inherit the same license (de Laat 2005).

Data integration principles that were consistently underemphasized in existing frameworks include scientific rigor and pragmatism, a core element of utility (Table S1.1; Figure S1.1). Experts indicated that scientific rigor in data integration includes explicitly documenting NTD collection methods and study design, clearly communicating appropriate and inappropriate (re)uses of findings based on those methods, and estimating uncertainty in findings. Utility ensures that data integration is well suited to policy and management decisions by providing decision-makers access to data and findings, tailoring data integrations to respond to decision needs, and offering guidance and support for responsibly applying data integration to decisions under uncertainty.

Principles do not immediately translate into effective real-world implementation. For example, for FAIR, the Interoperability and Reusability principles have been particularly challenging to achieve, relative to Findability and Accessibility (Jones et al. 2019), in large part due to the slow adoption and expansion of community-endorsed metadata standards (Bagstad et al. 2025). We reviewed how these four broad principles—scientific rigor, utility, metadata, and reuse—have been implemented in the field, in seven real-world case studies, alongside our paradigms (Table S1.2).

4 | Case Studies

We assessed seven real-world case studies across diverse regions, users, biomes, use cases, and sensors to understand the state of NTD integration for biodiversity monitoring and conservation. We compared these experiences with our paradigms and principles (Figure 2). For brevity, the case studies and the sensors employed are described in Figure 2, and further detailed in Supplement 2.

5 | Paradigms and Principles in Action: Case Studies in NTD Integration

5.1 | Paradigms in Case Studies of NTD Integration

We propose that by understanding the paradigmatic approaches to integrating NTD in multiple real-world case studies, rather than theoretical or one-off explorations, we can better identify challenges, opportunities, and next steps for replication and scaling. Analyzing these paradigms through the lens of real-world case studies provides an indication of the maturity or novelty of integration approaches, and where there is need for new tools and guidance to scale and build confidence for practical application in business and policy. Table 1 summarizes the challenges, opportunities, and next steps identified in these real-world case studies through the lens of our paradigms. The analysis resulting in Table 1 was performed by the authors, which include researchers involved with each case study site, as well as NTD providers, NTD platform developers, modelers that use NTD, and other conservation practitioners that use NTD. These takeaways are intended to provide the foundation for an actionable framework that provides useful guidance to all these categories of practitioners.

Our seven case studies applied different paradigms to achieve their purposes, and many adopted multiple paradigms (Figure 2). Consilience, the only paradigm applied by all seven case studies, most often consisted of exploration to identify relationships between multiple types of NTD (e.g., BDFFP, Gulf of California, Osa). In many cases, this entailed assessing broad-area satellite-derived datasets alongside point-based data from in situ sensors. In three cases (ZWW, Osa, Western Ghats), consilience led to delineation of high-quality or active habitat by comparing land cover or ecosystem structure, species movement, and/or species observations. In two others (Alto Mayo, South Estuary Concession), it contributed to the characterization of species diversity and community composition, identifying high conservation value sites. This paradigm presents the lowest-barrier approach, using side-by-side comparison of datasets without systematic or complex integration methods. However, challenges were identified, including insufficient data and inadequate guidance to summarize data for intercomparison.

Across this paradigm and others, mismatches in timing, scale, or resolution of datasets were a challenge. In many cases, this mismatch resulted from global spatially and temporally coarse satellite-derived products (designed for global research questions or monitoring goals) being challenging to pair with localized in situ data collected over finite periods for field campaigns (designed with differing local goals in mind). However, even among localized in situ data, timing mismatches and other sampling differences existed between different modalities.

The case studies indicate that consilience will be a primary way biodiversity insights are derived, particularly as in situ NTD

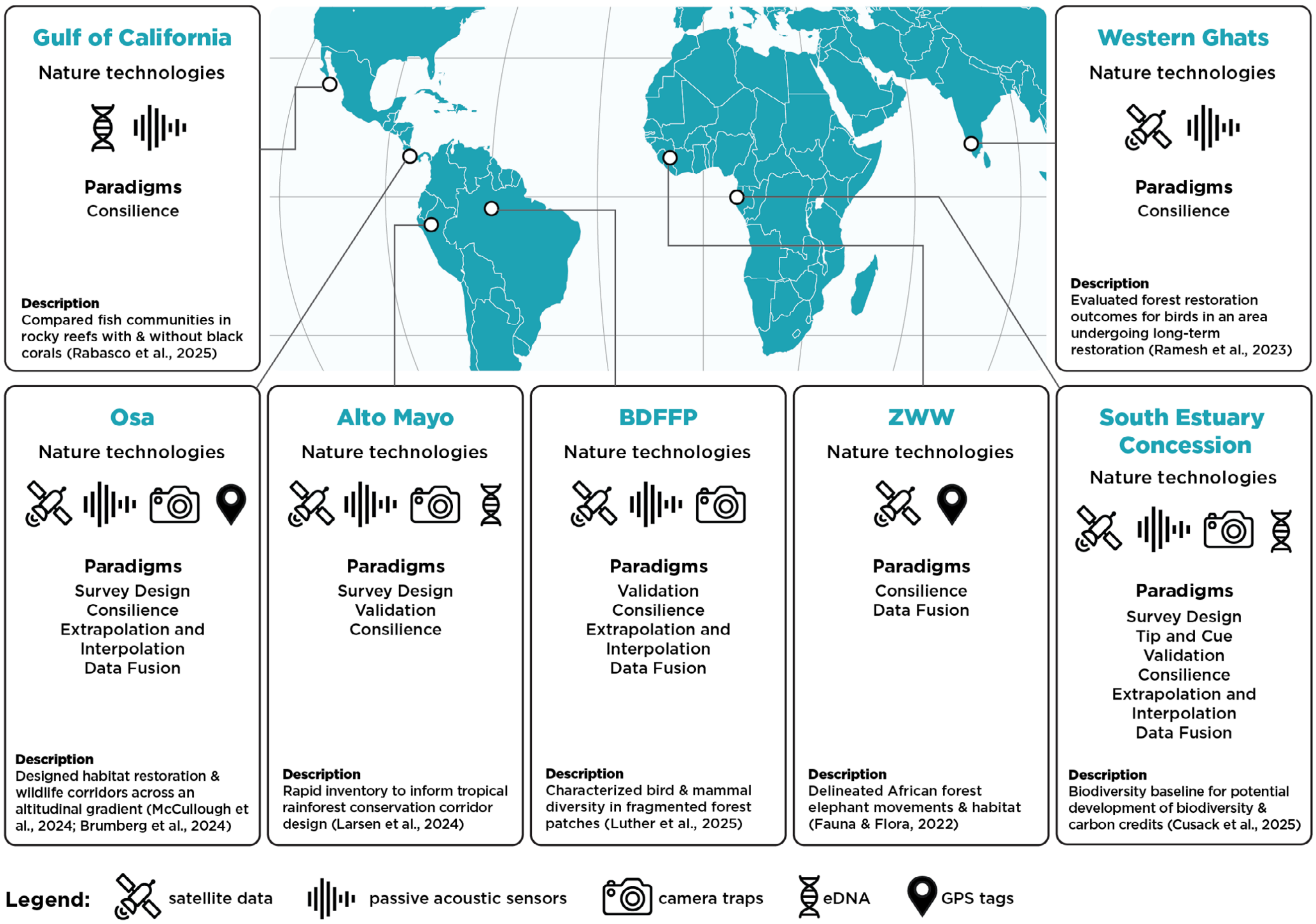

FIGURE 2 | Nature technologies and paradigms for data integration mapped to real-world case studies. Supplement 2 provides detailed case study descriptions, and Supplement 3 offers a comprehensive mapping of case study activities to paradigms.

proliferate, more studies are published, and satellite remote sensing datasets increase resolution (spatially, temporally, and spectrally), making them easier to relate to localized in situ data.

Consilience serves as an entry point for more sophisticated data integration. In several cases, consilience preceded other data integration paradigms, defining relationships that were then operationalized with interpolation and extrapolation or data fusion. In BDFFP, researchers explored space-based forest structure metrics alongside in situ-derived mean species occupancy before conducting quantitative interpolation from those established relationships across unsampled areas.

Elsewhere, South Estuary Concession interpolated a spatially continuous biodiversity layer using data from multiple sensors in situ. In Osa, NTD-derived habitat connectivity models were extrapolated both *spatially* to novel landscapes and *temporally* to predict wildlife habitat preferences in future climate scenarios. In these cases, the purpose of interpolation and extrapolation was to fill in data gaps and create an extensive spatial layer beyond the placement of site technologies.

Multiple case studies identified a lack of clear methodological guidance as a challenge for interpolation and extrapolation. There is an opportunity to develop systematic guidance for frequently requested workflows, such as extrapolating species diversity estimates based on characteristics like ecosystem structure. Several case studies expressed a strong interest in pursuing this paradigm, but noted that in situ data were not sampled densely or widely enough to facilitate high-confidence interpolation or extrapolation, pointing to an opportunity for the growth of this paradigm as these technologies decrease in cost and complexity.

Three cases (South Estuary Concession, Osa, ZWW) used data fusion, building on consilience and extrapolation by joining together NTD in a new product that was then used in follow-on analyses or decision-making frameworks, absent the original individual datasets. After extrapolating habitat preferences in Osa, researchers created a new connectivity surface layer to analyze "pinch points" where animal movement is being constrained (McCullough et al. 2024). In ZWW, satellite and GPS tag data were fused to produce a resource-use probability map that was leveraged in a new analysis to understand population-specific habitat preferences for forest elephants.

Data fusion seemed to be employed when different sensors provided complementary data that contributed to an overall indicator; for example, the creation of a multispecies occupancy model that leverages the ability of acoustic sensors to detect vocalizing birds throughout the canopy and the ability of camera traps to detect non-vocalizing mammals on

TABLE 1 | Challenges, opportunities, and next steps for nature technology data integration by paradigm, as identified by case studies.

Challenge	Opportunity	Next Steps	Paradigm(s)
Mismatches in timing, scale, and resolution between datasets produced by different technologies	Higher spatial, temporal, and spectral resolution satellite remote sensing datasets available at broad scale, for integration with in situ technologies	Connect conservationists to open-access, high-resolution satellite data, coupled with training resources including example code and libraries	• Consilience • Interpolation and extrapolation • Data fusion • Survey design
Lack of widespread, co-occurring or densely sampled nature technology datasets	Increasing spread and duration of in situ nature technologies as they continue to decrease in cost; developing and testing more AI models and analytic platforms for big-data analysis of growing datasets	Support integrated multimodal data collection and connectivity for ecologists and conservation practitioners in the field in more sites and regions	• Interpolation and extrapolation • Tip and cue • Data fusion
Lack of methodological guidance and tools for operational data integration and conservation action	Systematizing guidance on workflows and models for conservation questions and goals based on documented case studies and peer review	Draw on existing expert communities (e.g., GEO BON, ISE, WILDLABS) to produce step-by-step, tangible guidance and roadmaps for specific paradigms	• Interpolation and extrapolation • Tip and cue • Data fusion
Absence of reference libraries for data comparison and emerging AI models associated with lower confidence and higher uncertainty, making it hard to incorporate in operating procedures	Building comprehensive reference libraries, guidance and tools to convey and manage uncertainty, and applying multiple nature technologies for confirmatory results	Incentivize the deposit of individual datasets into existing, standardized, accessible repositories of nature technology data (e.g., Wildlife Insights) and partner with citizen science platforms to target missing references and gaps in databases	• Validation • Tip and cue
Manual or complex workflows inhibit the use of integrated nature technologies for timely intervention	Automating workflows that integrate signals from multiple nature technologies to inform decision-making and action (e.g., change alerts)	Encourage opportunities for stakeholders to collaboratively develop data and API standards that support integration of multiple data streams. Support open-source, well-validated AI models for use across the community	• Data fusion • Tip and cue

the forest floor. New AI approaches present opportunities for integrating multiple NTD via the data fusion paradigm (Sastry et al. 2024; Trantas et al. 2025), such as multimodal habitat representations from satellite imagery and ground-level camera-trap imagery for new occupancy layers (Haucke et al. 2026). However, similarly to consilience, input datasets with coarse spatial and temporal resolution remain a challenge. As with interpolation and extrapolation, denser sampling of validated in situ data inputs and more comprehensive reference libraries will increase the confidence of layers produced by data fusion.

With growing use of remote sensing and AI models, validation was identified by case studies as being increasingly important to confirm the accuracy of species status and trends. Validation was used in three case studies. eDNA findings were verified with passive acoustic monitoring detections (Alto Mayo) and camera trap identifications (South Estuary Concession). The purpose was to confirm a lower-confidence indication in the eDNA data with higher-confidence, location and time-stamped camera trap or acoustic data. In BDFFP, in contrast, researchers used this paradigm to confirm a satellite-based proxy for species richness (i.e., structural diversity) with more direct data from camera traps and acoustics.

Three case studies used survey design (Alto Mayo, Osa, South Estuary Concession), primarily by informing sampling design of in situ sensors (e.g., camera traps) using a satellite-derived map. In some cases, satellite data were only one input among many to inform site surveying (e.g., GPS tags or expert input). The purpose tended to be to ensure robust survey design with representative sampling. Opportunities identified by case studies included the adoption of higher temporal and spatial resolution maps of landcover, ecosystem condition, or habitat suitability to improve the application of NTD to survey design.

By contrast, only one case study employed tip and cue. In the South Estuary Concession, eDNA data identified threatened species, providing a "tip" that "cued" deployment of a new set of camera traps and acoustic sensors targeting species for further management recommendations. Other case studies indicated challenges to applying this paradigm, including lack of access to the desired technologies and an absence of easily applied methodologies or automated workflows. The example from South Estuary Concession was manual; the "tip" was detected in data from a sensor not explicitly established for that purpose, and the cued response was an opportunistic response activity. An opportunity includes use of automated "tip" alerts set up specifically to search for certain phenomena, which then mechanistically "cue" additional monitoring or enforcement actions, such as cueing UAVs tipped by satellites or GPS collars to mitigate poaching of elephants and rhinos (Dorfling et al. 2021).

5.2 | Principles in Case Studies of Nature Technology Data Integration

Case studies varied in their application of four principles: metadata standards, interoperability, and machine-readability; use rights and licensing for access and reuse of data integrations; scientific rigor in design, documentation, and code; and utility of data integration for real-world decision-making. We found strong operationalization in many areas. Almost all case studies included core metadata fields and archived data and metadata in machine-readable formats. Most cases had clear licensing and use rights communicated with datasets. All followed established methods for collecting and integrating NTD and ensured guidance from scientists and tech specialists. Some cases, like Western Ghats, BDFFP, and Osa, exhibited very detailed documentation on methods and algorithms, enabling responsible reuse, repeatability, and application to conservation decisions. Most case studies were designed for uptake in management or policy decisions and demonstrated active use of findings; two had planned future use, and only one had no clear trajectory for uptake in decision-making.

However, implementation of data integration principles was not uniform. For metadata, only two of seven case studies (BDFFP and South Estuary Concession) were fully annotated using Darwin Core to enable integration into GBIF and other conservation datasets. Two were partially aligned (Osa and Western Ghats), and the remainder did not use Darwin Core, though all could be annotated later. Access for reuse was not standardized: three out of seven case studies had internal, proprietary data archiving; in two cases, this was related to data collection for clients and inclusion of sensitive species or locations. Four case studies either archived in public-facing repositories with open licenses or intended to. Sometimes code was shared for AI models and statistics (e.g., via Zenodo for the Gulf of California and Western Ghats, see Supplement 2), but not by most. Although most case studies addressed metadata and scientific rigor, it was not clear that they all effectively communicated constraints on interpreting and reusing resulting data and findings (e.g., limitations on calculating species richness, presence, or movement due to sensor placement, battery life, or technical specifications).

Scientific rigor was clearly considered in the use of NTD. We did not find evidence for concern that the introduction of NTD would significantly reduce scientific rigor. Data access for reuse remains murky despite increasing adoption of licensing and archiving standards. Reuse patterns among the case studies ran the gamut from closed, private storage to re-sharing on public platforms. Importantly, however, two cases that had proprietary internal archiving allow access to data upon request, with documented secondary uses for conservation status assessment.

Looking forward, we support the continued evolution and more widespread use of metadata and archiving standards for newer data formats, like video, derivative datasets, algorithms, cloud-optimized file formats, and multimodal repositories. We encourage clearly communicating the methodology and purpose of data collection and implications for appropriate reuse (Trochim and Roy 2025). Opportunities remain for setting community-wide agreements on ethically sharing key data while growing the sector through commercial efforts, reducing challenges to access and capacity in the Global South, and engaging with local and Indigenous knowledge holders.

6 | Conclusion and Future Directions

The need for integrated biodiversity monitoring arises from a simple but persistent challenge: no single sensor can capture the complexity of ecosystems. Both the literature and our case studies indicate that when drawn from multi-sensor mixes and combined with traditional field observations, NTD enables richer understanding and predictive capacity beyond what any single dataset offers, aligning more with the needs of local management, global policy, and corporate reporting. As a next step toward these benefits, the authors and other technologists, researchers, and practitioners are building on this work to craft further detailed methodological guidance on individual paradigms.

However, fully realizing the potential of NTD will depend not only on technical advances, but also on the collective commitment of the broader community (Ramage 2021). It will require alignment across sectors (including civil society, the private sector, philanthropy, and government), consideration of IP constraints, and coordination among stakeholders operating at local, regional, and global scales to understand different data collection goals and knowledge gaps. Additionally, convergence on common standards, open or shared infrastructure, and mutual trust will be essential.

If we can bring these elements together—linking diverse datasets, harmonizing methods, and fostering collaboration—the payoff will be profound. Integrated monitoring could enable high-confidence global assessments, actionable early warning systems, instructive forecasting and management tools, and robust, repeatable metrics to underpin emerging nature finance mechanisms. These principles and paradigms are intended to provide a foundation for realizing integrated biodiversity monitoring for all stakeholders to help guide research and action.

Author Contributions

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Disclosure

Statement on Inclusion: Our manuscript is a conceptual analysis of principles and paradigms for biodiversity monitoring, and as such, there was no local data collection related specifically to this paper. However, in our conceptual analysis, we acknowledge key opportunities for increasing nature tech by reducing barriers to access and capacity in the Global South, and engaging with local and Indigenous knowledge holders. Additionally, we analyze our principles and paradigms through real-world case studies. We selected these case studies to represent diverse regions, users, biomes, use cases, and technologies. Many of the publications and datasets from these case studies (which we cite in the paper and supplements) include coauthors from the country in which the original case study data were collected. However, in future publications, workshops, and discussions building on our initial frameworks, we recognize the need to further incorporate voices from the Global South where all of our case studies are located and where significant nature tech data for biodiversity monitoring is collected.

Data Availability Statement

All work information associated with the conceptual development of the paradigms and principles can be found in the manuscript or Supporting Information of this work. Information on the data availability for the case studies is below: *Alto Mayo case study*: Final report, containing open data https://cdn.sanity.io/media-libraries/mlmEWUxEY7eQ/files/3272c4f1c33fb841032cf42f2954b68764fa26f5.pdf?sfvrsn=e66add1e_3. *BDFFP case study*: The metadata associated with acoustic and camera trap detections (in Darwin Core format), as well as the preprint of the corresponding scientific paper, can be accessed here https://dashboard.wildmon.ai/project/bdffp. *Gulf of California case study*: The raw genetic sequences can be found in GenBank: https://www.ncbi.nlm.nih.gov/sra/PRJNA1260186. All the files and codes related to the original study can be found at: https://doi.org/10.5281/zenodo.16540403. *Osa case study*: Data and code from "Integrating high-resolution remote sensing and empirical wildlife detection data for climate-resilient corridors across tropical elevational gradients": https://zenodo.org/records/11122373. Data and code for "Mapping climate adaptation corridors for biodiversity—A regional-scale case study in Central America": https://zenodo.org/records/11150568. Landcover maps from "Increasing Forest Cover and Connectivity Both Inside and Outside of Protected Areas in Southwestern Costa Rica": https://figshare.com/articles/dataset/Osa_Peninsula_LULC_Maps_1987_1998_2019/19337912?file=34343183. *Western Ghats case study*: Code and analyses necessary to reproduce this study: https://github.com/vjjan91/acoustics-Restoration. *ZWW case study*: Code necessary to reproduce this study is adapted from Prof Elie Gurarie (University of Maryland), "Working with Movement and Spatial Data in R": https://terpconnect.umd.edu/~egurarie/research/NWT/Step06_RSF_PartI.html.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Supplement 1**: Principles. **Supplement 3**: Case Study to Paradigm Mapping. **Supplement 2**: Case Study Background.