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Accelerating forest landscape restoration monitoring in Africa: informing tangible actions from a practical perspective

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Forest landscape restoration (FLR) is purported to achieve socio-ecological outcomes in addressing the interlinked crises of deforestation and land degradation, biodiversity loss, and climate change. While several instruments exist to substantiate progress toward such outcomes and the effectiveness of FLR interventions, various challenges hinder monitoring. This study uses a proposed analytical framework that articulates elements of restoration monitoring feasibility to examine the realistic application and convenience of proposed restoration monitoring instruments, focusing on Africa, where continental-level flagships are scaling up restoration actions. We applied a critical content analysis guided by our analytical lens to secondary data collected from top-down and bottom-up monitoring instruments. A survey was also used to explore the level of knowledge and identify the tools and guiding frameworks used by restoration practitioners, which we analyze using descriptive statistics. Our analysis reveals 34 restoration monitoring indicators spanning biophysical, socio-economic, and institutional realms, along with 196 related metrics. The strong emphasis on biophysical metrics relative to socio-economic and institutional ones reflects unbalanced attention to sustainability dimensions. Our analysis of the identified 39 monitoring tools and guiding frameworks indicates that most require essential (super)infrastructural capacities, appropriate knowledge, and tailored skills for their effective use. Confirming this, the survey reveals low awareness and use of these monitoring instruments, with the three most cited limiting reasons being inadequate funding, infrastructure deficits, and inadequate technical expertise. Overall, the results reaffirm the need for pragmatic, low-cost, and accessible instruments to advance FLR monitoring in Africa, and we offer actionable suggestions for some limiting challenges.

Key words: Africa, (cap)abilities, feasibility, indicators and metrics, restoration monitoring, (super)infrastructure, tools and guiding frameworks

Implications for Practice

- Indicators and metrics to monitor forest landscape restoration should reflect balanced sustainability dimensions, including ecological, social, and institutional ones.
- The development of restoration monitoring instruments should be contextually relevant and appropriate, low-cost, and pragmatic (accessible and usable).
- Integrating participatory, bottom-up, and top-down approaches in the conceptualization of restoration monitoring instruments will increase their practicality while also reflecting Indigenous and local knowledge systems.
- Technical capacity building, skill-oriented training and education, and low-cost technological and (super)infrastructural development and improvement will accelerate the use of restoration monitoring instruments.

Introduction

Forest landscape restoration (FLR), a people-centered approach to ecosystem restoration, has received global attention for its potential to contribute to addressing forest loss and degradation and biodiversity loss while supporting sustainable development and climate change responses (Besseau et al. 2018; Erbaugh & Oldekop 2018; Djenontin et al. 2021). FLR is an integral part of the global ecosystem restoration policy (UNEP 2021), anchored in the UN's 2021–2030 Decade on Ecosystem Restoration (Young & Schwartz 2019; Aronson et al. 2020; FAO

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et al. 2021), which elevates earlier intergovernmental declarations such as the Bonn Challenge and the New York Declaration on Forests that set goals to restore a total of 350 million hectares (ha) of land globally by 2030. In Africa, 34/54 countries have pledged to restore 100 million hectares of degraded landscapes by 2030 under the AFR100 initiative—the Africa-level FLR flagship (Djenontin et al. 2020; Mansourian & Berrahmouni 2021). While practical embodiments of FLR in Africa are context-dependent, with a variety of restoration activities, the restoration goal is to improve multifunctional landscape conditions, with biodiversity recovery and greater ecosystem services for enhanced food and livelihood security and climate resilience (Djenontin et al. 2020; Nelson et al. 2024).

Monitoring restoration efforts is integral to understanding related achievements and demonstrating potential success and broader socio-ecological impacts while learning lessons. Monitoring, as a continual process, can catalyze adaptive restoration implementation and social learning for course correction actions, a core principle of FLR. More importantly, monitoring can generate insights into the effectiveness of restoration approaches and related outcomes (Stanturf et al. 2017; Mansourian & Stephenson 2023). This requires appropriate process-related and result-oriented indicators and metrics to monitor, as well as relevant and accessible tools (Dey & Schweitzer 2014). Establishing instruments to track and assess the progress of any intervention is paramount.

However, monitoring restoration is challenging, both regarding the tools proposed and the actual (and many) indicators to measure (Guariguata & Evans 2020; Mansourian & Stephenson 2023). First, while efforts have been put into articulating monitoring instruments (Mansourian & Stephenson 2023; Tedesco et al. 2023; Löhr et al. 2024), including collaborative monitoring approaches (Guariguata & Evans 2020), many of these monitoring instruments are found to not reflect the principles undergirding FLR (Gutierrez et al. 2022). Also, where they exist, the implementation of monitoring instruments is complex and challenging in practice and, as such, impedes the effective assessment of restoration actions and outcomes (César et al. 2021; Gutierrez et al. 2022; Jurjonas et al. 2024). Second, while restoration indicators are now proliferating (Zamora-Cristales et al. 2020; de Oliveira et al. 2021; FAO & UNEP 2022), most of them are difficult and often impractical to measure at local scales due to inadequate capacity and infrastructure (Kirschke et al. 2020; Mansourian & Vallauri 2022; Achieng et al. 2023). Several criteria have been proposed to guide the selection of appropriate indicators and metrics at the relevant scale for restoration monitoring, but these do not always consider local technical and infrastructural capabilities that can impede their application (Dudley et al. 2018; Evans et al. 2018; Mansourian & Stephenson 2023). Such constraints are true for many of the African countries involved in restoration implementation.

The appropriateness of FLR indicators and metrics put forward and their actual measurement using accessible tools has received little attention (one exception being Mansourian & Vallauri 2022). For instance, questions still remain about the adequacy/relevance of the plethora of indicators vis-a-vis the various contexts and goals of restoration (de Oliveira et al. 2021) and how feasible it is to measure them, notably what appropriate metrics to assess and with what tools, as well as the accessibility of the tools. Many proposed indicators appear theoretical without clear metrics and are often cumbersome to measure because of limited access and knowledge of relevant tools. Also, the proliferation of indicators (e.g. ecological, social, economic, governance, etc.) is overwhelming to professionals and may not be contextually appropriate for landscapes being restored (Convertino et al. 2013; Evju et al. 2020; Fromont et al. 2024). Similarly, tools abound for measuring indicators, but they tend to be complex and prohibitive, with some having no clear specification about the indicators they can help to measure (Mansourian & Vallauri 2022).

In this context, our research examines the relevance and practicality of FLR monitoring instruments, drawing on elements of feasibility space as an analytical lens and a survey of 38 restoration practitioners across Africa. We analyzed identified restoration monitoring guiding frameworks and tools, and indicators and metrics, addressing the main question: *What measurable forest restoration indicators are compatible with the limited infrastructural and technical (cap)abilities in African contexts, while being adequate to capture restoration outcomes, and what tools are relatively accessible to use and collect this data*. We answer the following sub-questions: (1) How relevant are existing FLR indicators based on multidimensional feasibility? (2) How accessible and usable are monitoring tools based on feasibility principles? (3) What pragmatic approach and actions can be leveraged to reduce challenges to accelerate FLR monitoring?

Our study stresses that while the indicators reflect the three pillars of sustainability, there is a remarkably shallow focus on metrics beyond biophysical/ecological and economic dimensions. We note especially a limited reference to indicators and metrics that track cultural and institutional changes being induced compared to the economic effects through job creation. Furthermore, the study offers some middle-range, FLR monitoring instruments (indicators, metrics, and tools) that consider the limited (super) infrastructural, technical, and technological (cap)abilities in African contexts, while emphasizing technological development, technical capacity building, and skill-oriented training and educational needs as paramount institutional actions to invigorate restoration monitoring efforts. By examining the pragmatic dimensions of proposed monitoring instruments, our study offers actionable insights for some of the challenges limiting efforts to demonstrate outcomes, learn lessons, and scale up practice from the growing restoration interventions in the African region.

In the remainder of the paper, we articulate the analytical framework in Section 2 and describe the methods in Section 3. We present our results in Section 4, answering the three specific research questions, and finally we discuss our findings in Section 5.

Framing Restoration Monitoring Feasibility Space

How feasible FLR monitoring is with existing indicators and tools can be seen as a subjective concern, especially when there is no agreement on how to operationalize and assess feasibility. The feasibility concept has been variously defined, yet there has not been a consensus on what it is and ways of measuring it (Gilabert & Lawford-Smith 2012; Jewell & Cherp 2023)—a situation that could hinder the trajectory of developing consistent knowledge production in a specific field (Stern et al. 2023). Gilabert and Lawford-Smith (2012) simply explained feasibility as the ability to follow through with an outcome or goal, aligning with another conceptualization that relates to the capacity to achieve a desired outcome (IPCC 2022). Jewell and Cherp (2023) defined it as "do-able under realistic assumptions" and Singh et al. (2020) defined it from the angle of possibility/desirability of an option. While the term is often used in the "everyday" English language and even in technical or scientific space, there hasn't been any conscious effort to standardize its meaning and usage. To address such ambiguity, we develop an analytical framework that builds parallels to the concept of feasibility space (Jewell & Cherp 2023), but with nuances applied to the realm of FLR. Our proposed restoration monitoring feasibility space framework integrates principles and dimensions of feasibility (Fig. 1), whereby the dimensions of feasibility help to examine the relevance/adequacy of indicators, including related metrics, and the principles of feasibility allow the analysis of the accessibility, relative suitability, and ability to use various tools proposed to collect data for the indicators according to technical and super/infrastructural capacities.

Dimensions of Feasibility

We draw on the Intergovernmental Panel on Climate Change (IPCC) multidimensional feasibility assessment framework that reflects interconnections and synergies between several factors. Such a multidimensional framework put forward six dimensions to examine climate options, including geophysical, ecological/environmental, technological, economic, socio-cultural, and institutional (Singh et al. 2020; Brutschin et al. 2021; Williams et al. 2021). Most often, these dimensions are operationalized with either generic or specific indicators (Jewell & Cherp 2023). Considering restoration, many already proposed indicators (and metrics) can be categorized across similar dimensions (Fig. 1), which are considered as the dimensions that restoration monitoring should capture (Viani et al. 2017; Mansourian & Vallauri 2022).

However, given the plethora of indicators and inconsistencies across associated metrics, determining relevant ones toward identifying middle-range, feasible (in terms of measurement) indicators can help to address the challenges currently faced in restoration monitoring (Mansourian & Stephenson 2023). Beyond just the frequency of the categorized indicators and their metrics, which indicate their relative importance, our feasibility assessment adds two additional parameters across the restoration monitoring dimensions. The first parameter is the adequacy to capture restoration outputs and/or outcomes as opposed to just inputs, and the second parameter is the concurrent occurrence of identified indicators and metrics between what we deem as "top-down," globally driven indicators and "bottom-up," project-driven indicators portfolios. Top-down indicators are those broadly framed and globally sourced indicators across the multiple dimensions of restoration monitoring, including ecological, biophysical, social, economic, and institutional (Buckingham et al. 2019; Zamora-Cristales et al. 2020; FAO and UNEP 2022; World Conservation Union 2022; GRO 2023). Bottom-up indicators are those emerging from implementations of various restoration projects, reflecting also multiple dimensions of restoration monitoring (see Mansourian & Vallauri 2022).

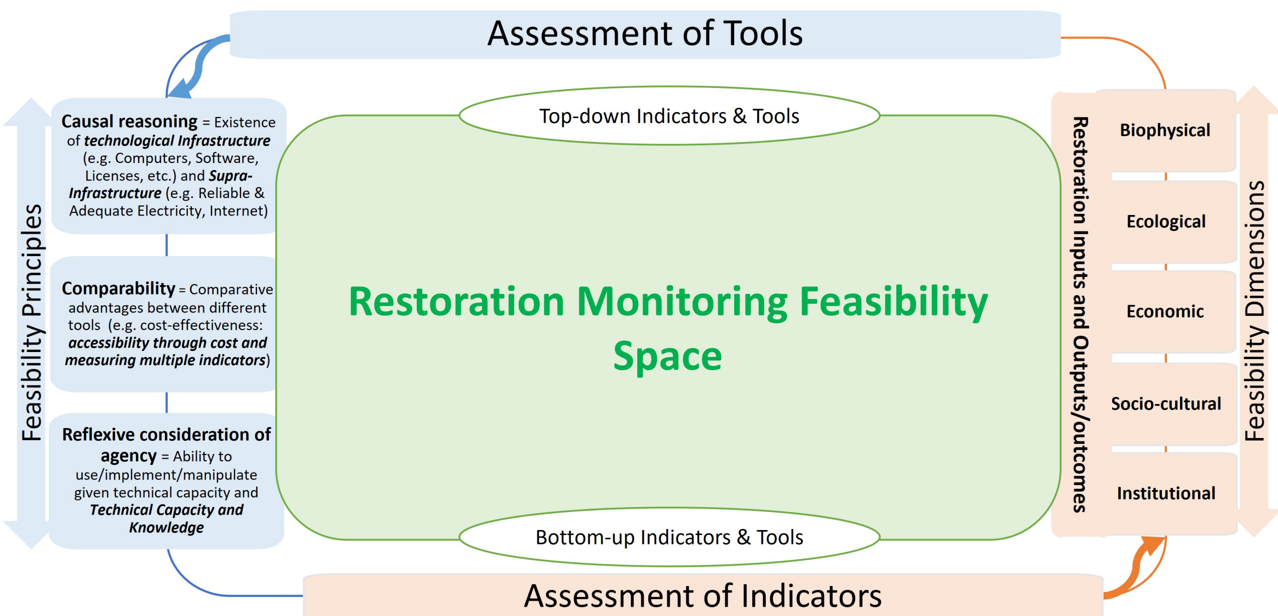

Figure 1. A conceptualization of feasibility of restoration monitoring indicators and tools.

Principles of Feasibility

Several restoration monitoring tools are proposed in the literature. To examine the feasibility of using such tools, we draw on the three most often advanced principles of scientific feasibility analysis in the literature (Jewell & Cherp 2020, 2023; Stern et al. 2023). A sound feasibility assessment can rest on causal reasoning, comparability, and reflexive consideration of agency (Fig. 1). First, following causal reasoning logics that infuse realistic perspectives, we argue that a monitoring tool would be considered feasible to use or not if there are enabling or disabling conditions allowing or preventing its adequate use. In the case of restoration monitoring tools, we considered, for example, the availability/existence of material infrastructure (e.g. computers, software, licenses, etc.) and supra-infrastructure (e.g. reliable electricity and adequate internet connection). Second, comparability underscores the comparative advantages between two or more tools and enables their comparative assessment. One example is to compare the cost-effectiveness of different tools to measure the same indicators and related metrics. We reduce the complexity of cost-effectiveness by focusing on tool accessibility through monetary costs (i.e. low or high costs) and the ability to measure multiple indicators. Third, reflexive consideration of agency focuses on the critical question of "feasible for whom, when, and where" (Gilabert & Lawford-Smith 2012; Jewell & Cherp 2020) suggesting that a tool will be feasible to use if targeted people/actors display the ability to manipulate it and/or implement associated tasks/activities in a given context to measure and communicate restoration indicators (Jewell & Cherp 2023). To be feasible would thus mean applicability within existing/available or enhanced technical capacity and knowledge. Therefore, feasible restoration monitoring tools would be in line with available or improved technical capacity and knowledge of their intended users (restoration implementers but also beneficiaries), who should be recognized as integral to monitoring needs. Our analysis does not intend to discredit any identified monitoring tools but rather to offer insights into what it would take to advance their practical use for the much-needed monitoring of current restoration efforts.

Overall, our restoration monitoring feasibility space integrates the practicality of both measuring indicators and utilizing the tools. It focuses on the relative do-ability of (1) collecting appropriate data/metrics to inform either directly or indirectly proposed indicators and (2) using appropriate tools for such measurements.

Methods

Data

We collected and reviewed secondary data on tools and indicators for monitoring restoration. Data on indicators and associated metrics were collected online through Google search, as well as through existing and available/accessible monitoring documents of restoration projects in Africa. Our searches were conducted between September and November 2023 and resulted in a pool of 12 global, higher-level monitoring instruments (herein top-down instruments) and five (5) project-level monitoring documents in Africa (herein bottom-up instruments). Table 1 illustrates the various sources of these instruments.

We also conducted an online survey on the knowledge and use of the restoration monitoring tools identified as part of the study. Survey questions focused mainly on awareness of the monitoring tools, their use, difficulties encountered when using them, their recommendation based on user experiences, training received (if any) on their application and use, length of the training, perceived training usefulness, trainers, and reasons for not using the tools (Supplements S1 & S2). We used purposive snowball sampling to reach respondents across Africa made up of country-level FLR focal points and other restoration practitioners implementing landscape restoration projects. We requested that respondents recommend other relevant practitioners in charge of restoration monitoring matters to also take the survey—a process intended to help us reach a wider audience. We distributed the survey via email and broadcasted it also using the AFR100 network of restoration practitioners on the continent. Overall, in addition to the 34 country focal points, we also identified 44 additional restoration practitioners involved in monitoring aspects, making the target audience 78. Our targeting approach is certainly not exhaustive, and the resulting sample size appears small. Yet, this reflects the limited number of practitioners who we identify to be somehow involved in restoration monitoring. The survey response rate was 49%, making the final working sample size 38. The survey completion rate was 84%. The survey was designed in Qualtrics

Table 1. Secondary data sources of the monitoring instruments identified for the study.

Location	*Source*
Global	Buckingham et al. (2019)
Global	WRI (2020)
Global	Vâgen et al. (2010)
Global	Cambridge Conservation Initiative (2021)
Global	IUCN - International Union for Conservation of Nature (2016)
Global	Gann et al. (2022)
Global	https://data.apps.fao.org/ferm/?lang=en
Global	https://restor.eco/?lat=26&lng=14.23&zoom=3
Global	https://docs.trends.earth/en/latest/
Global	https://resourcewatch.org/data/explore
Global	https://forest-water-tool.fao.org/
Global	https://auroramonitoring.org/#/
Malawi	Malawi Watershed Services Improvement Project (P167860)—Monitoring and Evaluation Plan—2021
Malawi	National Forest Landscape Restoration Strategy, the Ministry of Natural Resources, Energy and Mining, Malawi—2017
Kenya	Kenyan Forest and Landscape Restoration Monitoring Framework—2023
Madagascar	Fandriana-Marolambo landscape—Mansourian et al. (2018)
Tanzania	The East Usambara landscape—Mansourian et al. (2019)

in English, with embedded French translation to allow accessibility to both English-speaking and French-speaking respondents, given our target audience across Africa. We kept the survey active between16 January and 15 March 2024, and between 23 April and 24 June 2024. Ethical clearance for this study was obtained from the Institutional Research Board of the Pennsylvania State University (Supplement S3).

Analysis

We categorized indicators guided by the feasibility dimensions while noting their frequencies. The categories included ecological/biophysical indicators, socio-economic indicators, and institutional indicators. We then examined the metrics related to the categorized indicators for their relevance, focusing on their concurrent occurrence across project-level and global-level pools of indicators, paying attention to different framings that indicate the same metrics, as well as whether they capture outputs/outcomes compared to inputs.

We also critically assess the tools based on the feasibility principles as defined in our analytical framework, focusing on principles of causal reasoning, comparability, and reflexive consideration of agency. This allowed us to emphasize the strengths and limitations in their application/use. In addition, we analyzed the knowledge and use of the tools using the survey data. We used Microsoft Excel and RStudio version-2023.12.1+402 to analyze and visualize the survey responses, focusing mainly on descriptive statistics.

Finally, we apply an integrated analysis to propose middle-range, realistic restoration monitoring instruments that integrate pragmatic capacities to measure output indicators/metrics and constraints around accessibility/availability and (cap)abilities to use tools/frameworks in African implementation contexts. Specifically, we consider and synthesize all indicators with metrics assessing outputs from bottom-up monitoring instruments in addition to output metrics that were recurrent and concurrent in both bottom-up and top-down monitoring instruments. We then match the output metrics with the tools that were indicated as known, accessible, and relatively used to assist in accelerating monitoring in the meantime of potential increased training on other low-cost tools.

Study Limitations

We acknowledge that our analysis of the monitoring instruments is not differentiated for specific types of restoration or ecosystem types. This is because none of the instruments identified and examined were specific to particular restoration approaches or ecosystem types. This points to further research that needs to be considered, potentially with empirical data collection on the applications and relevance of these existing monitoring instruments on the ground. Despite this, our study provides a foundation on which restoration, irrespective of forest/ecosystem types, can be built upon, although monitoring may differ based on the forest/ecosystem types. Also, robust monitoring and evaluation systems are lacking in many restoration projects, which rely on top-down monitoring instruments that render monitoring unrealistic and ineffective in practice. In terms of international relevance, we note that because the scope of this study is limited to the African context, generalizing these findings may require some cautions. While the African continent provides a rich context for examining restoration initiatives, the diverse ecological, socio-economic, and political contexts of different regions necessitate a more nuanced approach, although we see several similarities with other places where restoration initiatives are being implemented.

Despite these limitations, we reiterate that our work contributes to the growing body of research that emphasizes the importance of robust, yet pragmatic and realistic, monitoring and evaluation in achieving successful restoration outcomes. A pervasive lack of monitoring and formal evaluation characterizes many restoration projects (Nilsson et al. 2016; Lindenmayer et al. 2022), complicated by complex, unrealistic monitoring instruments. Also, as Dudley et al. (2018) note, most monitoring systems have traditionally focused on ecological attributes, neglecting social attributes that remain on the fringes of monitoring protocols. We comprehensively illustrate this and articulate some implications along with actionable efforts to accelerate restoration monitoring. We also provide evidence that existing indicators are not matched with relevant tools to measure them, and we attempted to suggest how to fill such gap, while underscoring hindrances to address.

Results

Characterizing FLR Monitoring Indicators and Metrics

The indicators and metrics analyzed fall under three categories, including biophysical/ecological (11 indicators), socio-economic and cultural (15 indicators), and institutional/governance (8 indicators), with different frequencies that denote their relative importance (Fig. 2; Table S1). Each indicator is associated with one or more metric, with some indicators having a dozen or more metrics (Tables S1 & S2). The dimensions covered by these indicators and metrics reflect the pillars of sustainability, indicating an attention to capture restoration outcomes from a holistic socio-institutional-ecological approach.

Biophysical/ecological monitoring indicators of FLR interventions are heavily emphasized in both project-level (bottom-up) and global-level (top-down) monitoring instruments. By far, the most widely used biophysical indicator (22 mentions) is the "*area of land under restoration*" (Fig. 2). We counted a total of 18 metrics for measuring this indicator, including mainly tree density, size of tree, number of seedlings in nurseries, tree survival rate, net primary productivity (NPP), normalized difference vegetation index (NDVI), decrease in intensity of forest loss, and others (Table S2). The next most used indicators are "*protected area coverage, ecological diversity and connectivity*" (17 mentions), "*water quality and quantity*" (16 mentions), and *carbon sequestration* (12 mentions). Other biophysical indicators used, but relatively less referred to, included "improvements to soil stability/resilience," "land under soil and water conservation measures," and "area of vegetative riparian buffers established along major rivers and streams" (Table S1; Fig. 2).

Regarding socio-economic and cultural monitoring indicators of restoration, "*livelihood and economic benefits*" from restoration-related activities come first, with a frequency of

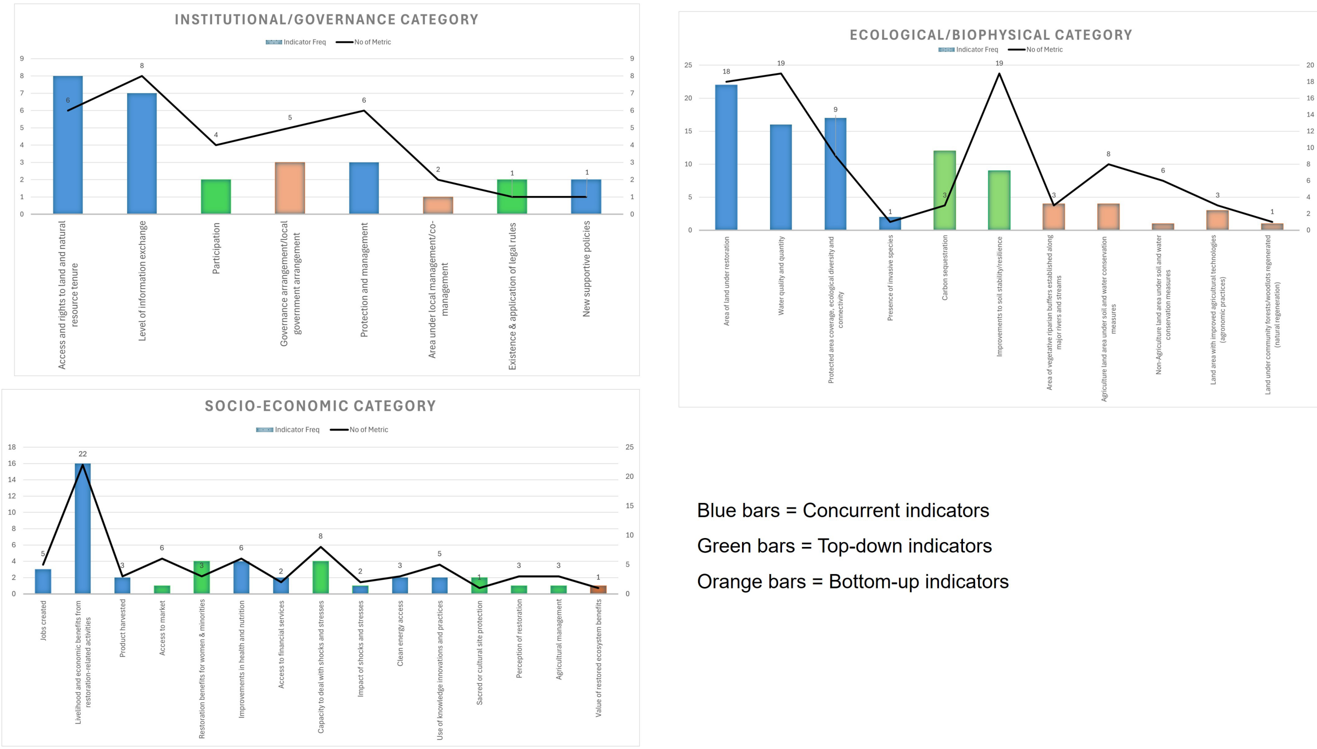

Figure 2. Identified restoration monitoring indicators and metrics by their categories.

16, followed by "*capacity to deal with shocks and stress*," "*improvements in health and nutrition*" and "*benefits for women and minorities*" (four mentions, each) (Table S1; Fig. 2). Some of the metrics suggested to measure the leading socio-economic and cultural indicator include the percent of income from restoration-related activities, number of non-timber forest products available on a sustainable basis, reduced water use in irrigation, the percentage change in household income levels and percent of farmers using water conservation practices (Table S2). Other socio-economic and cultural indicators identified include for instance "jobs created"; "product harvested"; "access to market," "access to financial services," and "access to cleaner energy" (Table S1; Fig. 2).

Institutional and governance indicators appear to be the least considered indicators. "*Access and rights to land and natural resource tenure*" is the most stressed among the institutional indicators (eight mentions), followed by "*level of information exchange*" with a frequency of seven (Table S1; Fig. 2). Metrics suggested to assess these indicators are the percentage of perceived land tenure security, percentage of land with officially designated use rights, hectares of land registered, percentage of farmers accessing extension services, number of farmers trained in different agricultural techniques, and number of farmers practicing sustainable land management practices (Table S2). Other institutional indicators identified include "participation," "(local)governance arrangement," "protection and management," "area under local management/co-management," "existence and application of legal rules," and "new supportive policies."

Relevance of Indicators and Metrics

We find that many of the metrics proposed to inform monitoring indicators are output-oriented. Out of the total 196 metrics analyzed, 136 measure restoration outputs while 60 are focused on measuring restoration inputs (Table S2). Biophysical indicators had many output metrics compared to input metrics. For instance, of the 90 metrics associated with the 11 biophysical indicators, 64 were output-oriented while only 26 would capture inputs. Socio-economic indicators had 59 output metrics compared to 14 input metrics. Institutional indicators were largely measured with input metrics. For instance, of the 33 metrics, 20 were measuring inputs while 13 were measuring outputs (Table S2). We summarize all the restoration output metrics identified in Table 2.

Regarding the concurrent occurrence of the indicators and metrics in both top-down and bottom-up restoration monitoring instruments, we find only a total of 16 output metrics, which together measure 9 indicators. Six output metrics are intended to assess biophysical indicators, another nine output metrics for socio-economic indicators, and one output metric is intended for institutional indicators (Table 2).

Practicability of the Tools and Guiding Frameworks for Restoration Monitoring

Both bottom-up and top-down monitoring instruments include 12 instruments that simply offer methodological guidance on conducting restoration monitoring, including processes of selecting indicators, which we refer to as a "*guiding*

Table 2. Output metrics of restoration monitoring indicators. BU, bottom-up; I/O, input/output; TD, top-down.

Category	*Indicators*	*Freq*	*Metrics*	*TD*	*BU*	*I/O*
Ecological/ biophysical	Area of land under restoration	22	Tree density	X	X	Output
			Size of tree	X		Output
			Percent area under tree canopy	X		Output
			No. of trees grown via assisted natural regeneration per area	X		Output
			Tree species diversity	X		Output
			Decline in forest fires in village land forest reserves and community-based forest reserves		X	Output
			Tree survival rate	X	X	Output
			Forest area restored, reforested or under improved management (ha)		X	Output
			Area under natural regeneration		X	Output
			World Conservation Union Red list species planted/regenerated		X	Output
			Amount of restored area showing an increase in Normalized Difference Vegetation Index (NDVI) and the Land Surface Water Index (LSWI) correcting for short-term climate effects.		X	Output
			Decrease in intensity of forest loss		X	Output
			Net primary productivity		X	Output
	Water quality and quantity	16	The level of water pollution	X		Output
			Diversity of aquatic life in rivers, streams, etc.	X		Output
			Stream flow and baseflow (hydrograph)	X		Output
			Runoff	X		Output
			Groundwater recharge rate	X		Output
			Infiltration/percolation rate	X		Output
			Flood occurrence	X		Output
			Flood extent (ha)	X		Output
			Water stress—proportion of water withdrawn compared to available water resources	X	X	Output
			Total suspended solids	X		Output
			Dissolved nitrogen	X		Output
			Dissolved phosphorus	X		Output
			Dissolved oxygen	X		Output
			Electrical conductivity	X		Output
			Acidity/alkalinity	X		Output
			Turbidity	X		Output
			Evapotranspiration	X		Output
			Local cloud cover and precipitation	X		Output
			Percentage in sediment yield	X	X	Output
	Protected area coverage, ecological diversity, and connectivity	17	Change in Red list index	X		Output
			Species richness	X		Output
			Mean nearest distance between habitat patches	X		Output
			Area of biodiversity corridors	X		Output
			Genetic diversity of vegetation	X		Output
			Connectivity indices for habitat patches	X		Output
			Protected area connectedness index	X		Output
			Key Biodiversity Area (KBA) targets/protected area coverage	X	X	Output
			Percentage increase in species/abundance of indicator species	X	X	Output
	Carbon sequestration	12	Aboveground biomass stock per ha per year	X		Output
			Estimated sequestered greenhouse gases	X		Output
			Soil organic carbon	X		Output
	Improvements to soil stability/resilience	9	Infiltration and percolation rate	X		Output
			Total nitrogen	X		Output
			Bulk density	X		Output
			Percent of farmers using soil conservation practices	X		Output
			Crust thickness	X		Output
			Penetration resistance of crust	X		Output
			Penetration resistance of subsoil	X		Output
			Aggregate stability	X		Output
			Reported levels of erosion	X		Output
			Visual observation and classification	X		Output
			Nutrient concentrations (nitrogen, phosphorus, and potassium)	X		Output

Table 2. Continued

Category	Indicators	Freq	Metrics	TD	BU	I/O
			Soil pH	X		Output
			Amount of fertilizer applied	X		Output
			Faunal density and richness	X		Output
			Microbial community richness	X		Output
			Soil respiration	X		Output
			Decomposition rate	X		Output
			Soil water storage	X		Output
			Soil erosion	X		Output
	Area of vegetative riparian buffers established along major rivers and streams	3	In (ha) or length (km)		X	Output
Socio-economic and cultural	Jobs created	3	No. of women, men and youth employed through restoration	X	X	Output
			Number of jobs	X	X	Output
			Number of individuals employed	X	X	Output
			Type of job (seasonal, casual, or occasional)		X	Output
			Job time frame (short and long)		X	Output
	Livelihood and economic benefits from restoration-related activities	16	No. of people who have increased knowledge and skills as a result of restoration	X		Output
			Percent of income from restoration-related activities	X		Output
			No. of households participating in restoration-related activities	X		Output
			No. of non-timber forest products available on a sustainable basis	X	X	Output
			Percent of farmers using water conservation practices	X		Output
			No. of people with access to water for productive use		X	Output
			Reduced water use in irrigation		X	Output
			No. of female farmers benefiting from an improved agricultural, aquaculture, forest-based produce		X	Output
			No. of small to medium scales dams developed		X	Output
			No. of rainwater harvesting structures developed		X	Output
			Length of feeder roads rehabilitated (km)		X	Output
			No. of river crossings/rural bridges rehabilitated		X	Output
			No. of market shades rehabilitated		X	Output
			No. of multiple-use water sources developed		X	Output
			Percentage change in household income levels		X	Output
			No. of household benefiting from alternative income-generating activities	X	X	Output
	Product harvested	2	Volume of timber harvested per year (kg/ha)	X		Output
			Yields of selected agricultural commodities supported by the project (%)	X	X	Output
			Proportion (%) of target farmers benefiting from an increase in production sold to the markets and/or an increase in income from marketed products		X	Output
	Access to market	1	Producer's share of final price	X		Output
			Share of roads in good condition	X		Output
			Rural road density (road length/total area)	X		Output
			Distance or walking time to nearest town	X		Output
			Rural access index	X		Output
			No. of producer groups/partnerships	X		Output
	Restoration benefits for women and minorities	4	Reduction in water burden	X		Output
			Reduction in energy burden	X		Output
	Improvements in health and nutrition	4	Percentage of undernourished	X		Output
			Average days per year household's food needs are not met	X		Output
			Life expectancy at birth	X		Output
			Under-5 mortality rate	X		Output
			Morbidity and mortality by cause of death	X		Output
			No. of households with food security improved	X	X	Output

Table 2. Continued

Category	*Indicators*	*Freq*	*Metrics*	*TD*	*BU*	*I/O*
	Capacity to deal with shocks and stresses	4	Share of production of top three crops	X		Output
			No. of crop species cultivated	X		Output
			Share of household expenditure on food items	X		Output
			Percentage of farmers with agricultural insurance	X		Output
			Percentage of households with property insurance	X		Output
			Percentage of population with health insurance	X		Output
			No. of doctors per 10,000 people	X		Output
	Impact of shocks and stresses	1	Percentage of people affected by climate-related natural disasters over the last 5 years		X	Output
			No. of buildings/dwellings affected by natural disasters		X	Output
	Clean energy access	2	Increase in number of households using improved stoves	X	X	Output
			Energy burden (expenditure)/price of woodfuel	X		Output
			Quantity of woodfuel produced	X		Output
	Use of knowledge innovations and practices	2	No. of speakers of indigenous languages	X		Output
			Percentage of household diet based on traditionally cultivated foods	X		Output
			Percentage of farmers that use traditional techniques	X	X	Output
			Percentage of households that use forest products for traditional non-food uses	X		Output
	Sacred or cultural site protection	2	Area of cultural/sacred land protected	X		Output
	Perception of restoration	1	Percentage of population that perceives forests as something to be protected	X		Output
			Percentage of population that values native species	X		Output
	Agricultural management		Percentage of households within targeted catchments engaged in sustainable land management practices		X	Output
	Value of restored ecosystem benefits	1	Expected annual earnings through ecosystem benefits from floodplains		X	Output
Institutional/ governance	Access and rights to land and natural resource tenure	8	Percentage of landscape with formalized land tenure rights that has clearly defined boundaries shown in publicly accessible maps	X		Output
			No. of farmers with tenure certificates		X	Output
			Ha of land registered		X	Output
			Ha of land adjudicated		X	Output
	Level of information exchange	7	Percentage of households sharing information/knowledge with other households	X		Output
	Governance arrangement/local government arrangement	3	Institutions annual average performance score (%)		X	Output
	Protection and management	3	Increased protection status		X	Output
			Management effectiveness score in most reserves		X	Output
			Ares FSC certified (Forest Stewardship Council)		X	Output
	Area under local management/co-management	1	No. of ha managed by community-based organizations		X	Output
			Total area of new village land forest reserves		X	Output
	Existence and application of legal rules	2	No. of illegal incidents	X		Output
	New supportive policies	2	New legislation/by-laws	X	X	Output

framework." The remaining 27 are specific *tools* that can be used for monitoring restoration. Using their descriptions and user manuals as applicable, our analysis of both sets based on our analytical perspective is illustrated in Table 3 (selected examples) and Table S3 (all identified tools and guiding frameworks).

Tools. Most of the tools analyzed require access to an electronic device (either a smartphone, a tablet, or a computer) and the availability of an appropriate internet connection to transmit data collected into a central database or to analyze the data. Only a few of the tools, such as the Regreening App and TreeMapper, can work offline when collecting data, but they will eventually

Table 3. Analysis of restoration monitoring tools and guiding frameworks based on the feasibility principles: Selected choices. F, framework; T, tool.

Name	*Type*	*Causal reasoning*	*Comparability*	*Reflexive consideration*	*Name*	*Type*	*Causal reasoning*	*Comparability*	*Reflexive consideration*
AURORA	T	Access to a computer and internet connection is required.	A comprehensive web-based system that comes with pre-determined indicators. It also requires the use of other tools for better results. It also involves extensive fieldwork. It is costly to use.	It can be tailored to the needs or desired outcome. It requires knowledge and expertise in all areas.	LandScale Assessment and Reporting Platform	T	An online platform that requires access to computers and the internet.	It comes with broad indicators that can be tailored to the needs of the landscape. However, it is not free. It comes with a cost depending on the level of assessment.	Users require expertise in Geographic Information System (GIS), social and environmental issues, as well as in data collection.
Global Forest Watch (GFW)	T	Access to a computer and internet connection is required.	Tool is only focused on forest loss. It is free but limited in its capabilities. And it is difficult to compare between landscapes.	It can not be manipulated. Data is independently captured. Focus landscape may not be included.	Ecological Recovery Wheels	T	Access to a computer and internet connection is required. Some assessment requires the use of remote sensing and field work.	It is a comprehensive tool that comes with pre-selected indicators and metrics. It can be used as a comparable measure between areas of interest. This is a free tool that can be accessed by anyone.	The indicators and metrics built in the tool can be calibrated to suit the area of interest. However, it requires extensive knowledge of ecology and social survey as well as in the use of remote sensing.
System for Earth Observation Data Access, Processing, and Analysis for Land Monitoring (SEPAL)	T	Access to a computer and internet connection is required. Requires add-ons or external data for support.	Suited for measuring forest cover. It doesn't come with indicators as such one will have to craft one to suit their goal. It is not comparable and also not cost-effective.	It is time consuming and requires extensive knowledge and skills in GIS, remote sensing, and coding. It is basically for understanding land cover changes and can be manipulated to suit any ecosystem.	Trends.Earth	T	Access to a computer and internet connection is required.	It is a free and open access tool designed for land cover changes. It comes with pre-existing indicators for comparison. It is integrated with QGIS, which is a free software.	Requires knowledge and skills in GIS, remote sensing, and ecology.

Table 3. Continued

Name	Type	Causal reasoning	Comparability	Reflexive consideration	Name	Type	Causal reasoning	Comparability	Reflexive consideration
Road to Restoration	F	Requires access to computer, internet as well as field assessment equipment.	A comprehensive guide capturing how to design restoration projects and monitoring framework, including indicators across ecological to governance. It can be used for comparing landscapes because of its standardized metrics.	It can be manipulated and used for a specific restoration goal. However, it requires extensive knowledge to use.	Ecological Integrity Assessment (EIA)	F	Access to a computer and internet connection is required. It also requires availability of experts and field assessment equipment.	Designed for assessing biophysical indicators, including vegetation, soil and hydrology, as well as its size and interactions with the surrounding landscape. It requires an extensive level of assessment.	It requires an extensive knowledge base in forest and ecology, remote sensing, and GIS. It can be designed to suit different forest landscapes.
Restoration Barometer	F	Uses existing infrastructure as it relies on national agencies for data collection.	A comprehensive guide to developing, monitoring restoration outcomes, and tracking multiple indicators. It relies on government sourced data making it cost-effective. Also, it allows for comparison of indicators at the global-level but not suited for the landscape level.	It cannot be manipulated for a given landscape even though national-based data collected is an aggregation of site-based data. It also requires knowledge in using certain tools and concepts.	Forest Inventory and Analysis Forest Monitoring Program (FIA)	F	Access to a computer and internet connection is required. It also requires availability of experts and field assessment equipment.	This tool was developed for the American forests but can be adopted for other regions. It can be used for comparison at the landscape level. It is not cost-effective and entails a lot of fieldwork.	It requires an extensive knowledge base in forest and ecology. It can be designed to suit different forest landscapes.

require an internet connection at the point of transmitting such data into a central database.

Besides, while not coming with pre-selected indicators, the majority of the tools offered focused mostly on measuring biophysical indicators, with less ability to capture socio-economic and institutional/governance indicators. Within biophysical indicators, the tools offered are best used to capture progress in the area of land under restoration from both geospatial parameters and survey-based metrics. This indicator was the most referenced biophysical indicator, as shown earlier. For instance, the Regreening App, the Global Forest Watch (GFW) platform, and tree cover mapping are tools that track the number of trees planted, nurseries established, tree cover, and other related metrics. Only a few of the monitoring tools comprehensively cover biophysical, socio-economic, and institutional/governance indicators at the same time. For instance, the Framework for Ecosystem Restoration Monitoring (FERM), the AURORA, and the Ecological Recovery Wheels are tools that go beyond ecological monitoring, in addition to providing specific indicators. Specifically, there are two dimensions of Ecological Recovery Wheels. One relates to the biophysical indicators of restoration, and the other focuses on the social and governance indicators of restoration. The wheels contain indicators and metrics that can be selected or adjusted to suit their restoration context.

Moreover, our analysis indicates that most of the tools for tracking restoration progress are free to use. Yet, many of these tools require specific, sometimes sophisticated, geospatial computing knowledge and skills to manipulate relevant data for different purposes. Examples include the System for Earth Observation Data Access, Processing, and Analysis for Land Monitoring (SEPAL) tool that requires adequate knowledge and skills in coding/programming for geospatial and remote sensing analysis as well as knowledge in ecology, such as collection and interpretation of biophysical properties. Interestingly, a few numbers of these tools need to be purchased—from licenses to "add-ons," which are relatively expensive and may render them unaffordable to use in contexts of low purchasing power. The LandScale Assessment and Reporting Platform is one such tool that is commercial and not freely available to use.

Furthermore, the tools analyzed are designed to measure indicators and metrics at a particular scale. While some focus on global, regional, and national scales, others are focused on the site and landscape levels. For instance, the Regreening App is focused on tracking the number of trees at the site and landscape levels, while the tree cover mapping tool can be used at both the landscape and national levels. The GFW platform is focused on global, regional, and national scales and may not be robust to capture restoration progress at the landscape levels. While the diversity of scale covered by the tools is a positive aspect, this can equally prevent or make it difficult to compare between indicators.

Guiding Frameworks. The 12 guiding frameworks analyzed provide guiding approaches on how to design appropriate indicators and metrics and the tools to employ when measuring such indicators. The guiding frameworks are comprehensive, considering biophysical, socio-economic, and institutional/governance indicators to track restoration progress. The Restoration Opportunity Assessment Methodology (ROAM) is one such comprehensive guide, which, while focused on identifying opportunity areas for restoration through a participatory, multistakeholder process, also provides indicators to monitor restoration progress. Only one guiding framework solely focused on the biophysical aspects of monitoring (e.g. the Land Degradation Surveillance Framework). In addition, all the guiding frameworks are freely available online for download without any cost. They also come with pre-selected indicators that can be tailored to a particular scale; hence, indicators can easily be used for comparative measures. Some of the guiding frameworks recommend explicit tools that may be used for measuring specific indicators, such as the area of land under restoration. One prime example is the Restoration Barometer, which recommends the use of tools such as Collect Earth, SEPAL, Restor, Trends.Earth, and the SER Recovery Wheels.

However, as part of data collection, most of the guiding frameworks require extensive data gathering for biophysical, socio-economic, and institutional indicators and metrics. For instance, the Restoration Barometer and the Sustainability Index for Landscape Restoration require extensive fieldwork to collect indicators on soil quality and carbon stock, biomass, water quality, management, equity markers, leadership, and the number of jobs created, among others. Such exigences suggest that adequate financial and human resources be allocated to monitoring activities.

Knowledge and Use of the Monitoring Tools and Guiding Frameworks

Our analysis of the survey data substantiates the limiting factors to the practical deployment of the tools and guiding frameworks for restoration monitoring as uncovered through the above assessment. Respondents have a limited awareness of the tools and guiding frameworks overall (Fig. 3).

Of the 27 tools and 12 guiding frameworks, respondents rated only seven tools and three guiding frameworks above average in terms of awareness, including, for example, the GFW (tool) and the Restoration Barometer (guiding framework). Instruments that respondents were less aware of include the Global Restoration Monitor, the Restoration Project Information Sharing Framework, and other not-so-common tools and frameworks (Table 4).

In terms of the practical uses of the instruments, recommendations based on user experience and training received, respondents also indicated low scores overall for the frameworks relative to the tools (Fig. 4). About 73% of the respondents used the tools, 67% would recommend some, while 69% received some sort of training on the tools. A relatively high number of respondents also received training on the guiding frameworks, but only a handful of them used and would recommend specific guiding frameworks.

Some top recommended monitoring tools include Forest Resource Assessment (9.09%); ArcMap/ArcGIS Pro (9.09%);

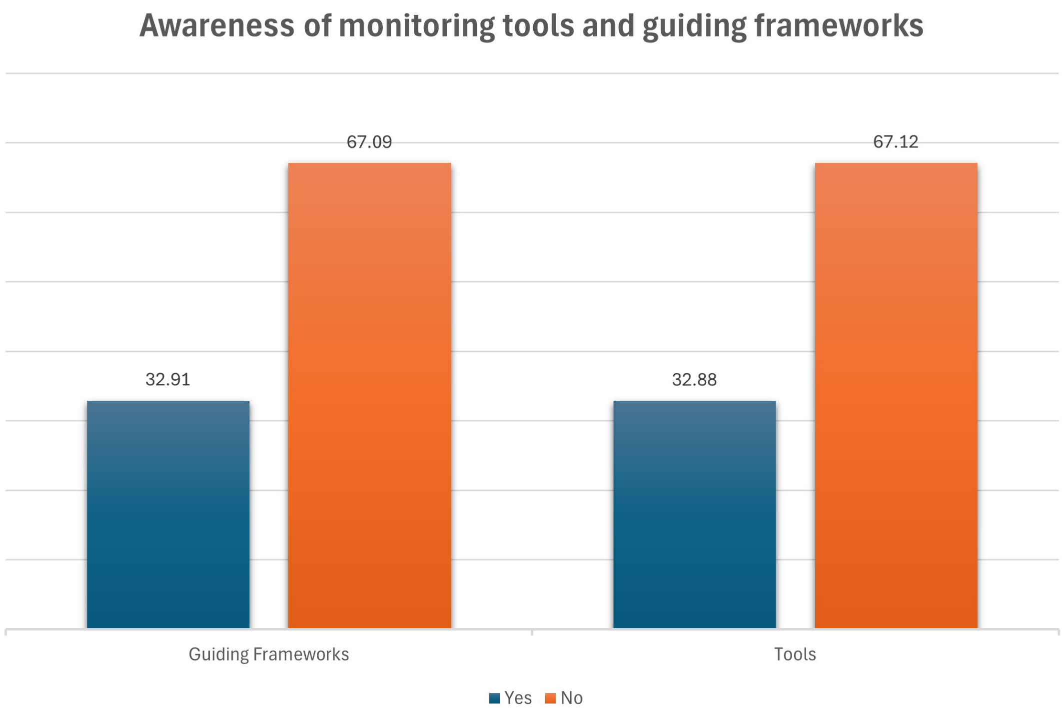

Figure 3. Awareness level of restoration monitoring tools/guiding frameworks among surveyed practitioners.

Google Earth/Google Earth Pro (9.09%); QGIS (8.18%); Tree Cover Mapping tool (5.45%), Collect Earth (5.45%). Regarding the guiding frameworks, respondents would recommend: the ROAM (7.27%); the Restoration Barometer (4.55%); the Road to Restoration (3.64%); the Restoration Project Information Sharing Framework (3.64%); the Forest Landscape Assessment Tool (FLAT) (2.73%).

For those who received some sort of training, 63% found them very useful and 11% rated them extremely useful, while 26% deemed them moderately useful. The majority of the respondents (53%) reported that most of the training received was run for less than a week, with only a few respondents (37%) reporting training lasting between 1 and 2 weeks. Respondents reported that training organizers are international organizations (25% reported), practitioners' organizations/ employers (25%), government (21%), non-governmental organizations (16%), and online (13%).

When asked about difficulties encountered to use the restoration monitoring tools and guiding frameworks, respondents noted three bottlenecks: (1) inadequate funding to access/buy the instrument, (2) infrastructure deficit for software/license and internet quality, and (3) inadequate technical expertise/ skills/capacity (Fig. 5).

Finally, respondents raised several factors preventing the complete use of the monitoring tools and guiding frameworks, including: (1) not sure how to access it [5]; (2) no/low awareness [3]; (3) lack of knowledge on the tool [4]; (4) lack of skills [5]; (5) no/lack of training [4]; (6) lack/insufficient expertise [2]; and (7) limited funding for capacity building [5]. As such, knowledge and training remain the highest constraints (Fig. 6).

Toward Middle-Range, Realistic Monitoring Instruments

Drawing integrated insights from the foregoing, our proposed middle-range restoration monitoring instruments (Table 5) include a total of 17 indicators with 48 output metrics, matched with the practical tools. These include three indicators with 13 metrics measuring biophysical/ecological attributes, nine socio-economic and cultural indicators with 25 metrics, and five institutional/governance indicators with 10 metrics. We note that, as a proposition emanating from a purposeful feasibility analysis as detailed transparently, we do not intend to be prescriptive with Table 5. This should be considered a realistic and pragmatic guide for restoration monitoring practitioners, especially for projects lacking monitoring frameworks and/or overwhelmed with practical challenges to implement complex monitoring frameworks. Adjustments to accommodating other metrics can be considered based on the contextual feasibility space, including potentially increased training on low-cost tools.

Discussion

What Insights on the Relevance and Appropriateness of Restoration Monitoring Indicators, Metrics, Tools, and Guiding Frameworks?

Our findings indicate that three main types of indicators and metrics are being tracked to understand restoration impacts, reflecting attention to sustainability dimensions. The reference to socio-economic indicators and metrics for restoration monitoring substantiates the quest to restore livelihoods and human well-being, while restoring landscapes, following the definition of FLR and the ambitions to achieve both ecological and social

Table 4. Most aware and unaware restoration monitoring tools and guiding frameworks among the surveyed practitioners.

Tools	*Guiding frameworks*
High awareness	
Google Earth/Google Earth Pro (86.21%)	Restoration Opportunity Assessment Methodology (ROAM) (72.41%)
Forest Resource Assessment (82.76%)	Restoration Barometer (62.07%)
ArcMap/ArcGIS Pro (65.52%)	Road to Restoration (55.17%)
QGIS (58.62%)	
Global Forest Watch (GFW) (55.17%)	
Tree Cover Mapping Tool (51.72%)	
Collect Earth (51.72%)	
Framework for Ecosystem Restoration Monitoring (FERM) (48.28%)	
LandScale (37.93%)	
Restor/Trend. Earth (34.48%)	
Low awareness	
Guinea LCLUC Explorer (93.10%)	Global Restoration Observatory (86.21%)
Veritree (93.10%)	Sustainability Index for Landscape Restoration (86.21%)
Global Safety Net (89.66%)	Carbon Estimator (86.21%)
Dynamic World (89.66%)	Forest Inventory and Analysis Forest Monitoring Program (79.31%)
Restoration Recovery Wheel (82.76%)	Forest Landscape Assessment Tool (FLAT) (79.31%)
Global Restoration Monitor (86.21%)	Land Degradation Surveillance Framework (LDSF) (79.31%)
Restoration Mapper (82.76%)	Ecological Integrity Assessment (EIA) (75.86%)
AURORA (79.31%)	Rapid Ecological Assessment (REA) (75.86%)
Regreening App (79.31%)	Restoration Project Information Sharing Framework (65.52%)
Resource Watch (79.31%)	

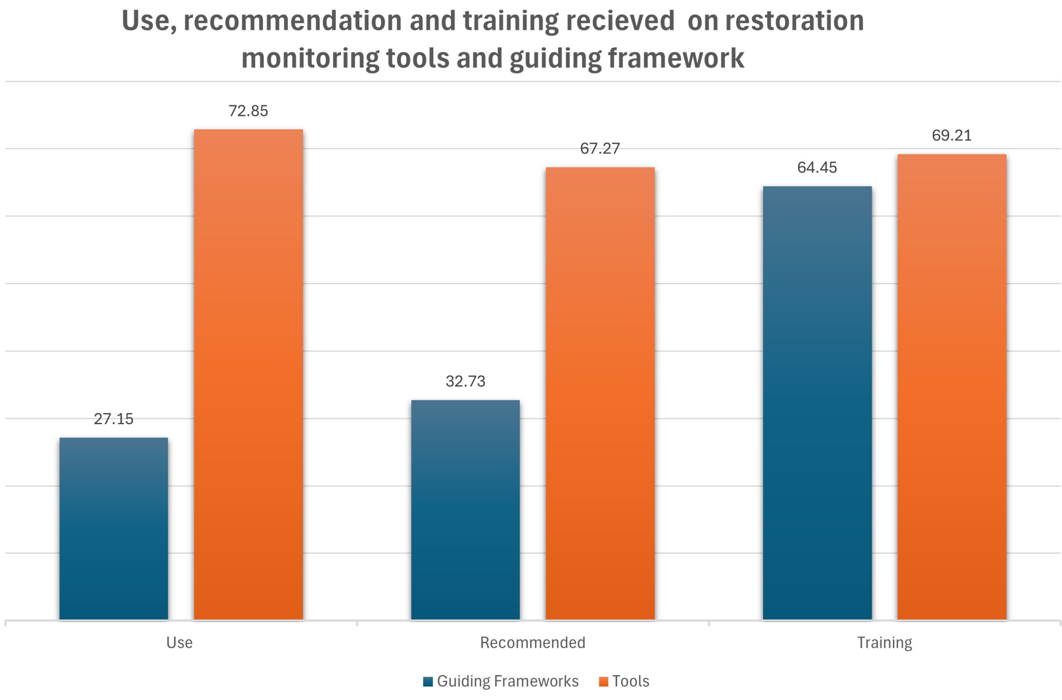

Figure 4. Use, recommendation, and training received on restoration monitoring tools/guiding frameworks among surveyed practitioners.

benefits (Erbaugh & Oldekop 2018). The reference to institutional and governance indicators as part of restoration monitoring suggests an improved consideration not only of restoration governance as fundamental but also of markers of social sustainability, such as metrics that inform on rights and equity issues (Löfqvist et al. 2023).

Yet, our findings also indicate that the attention to governance and institutional indicators is lower compared to a high

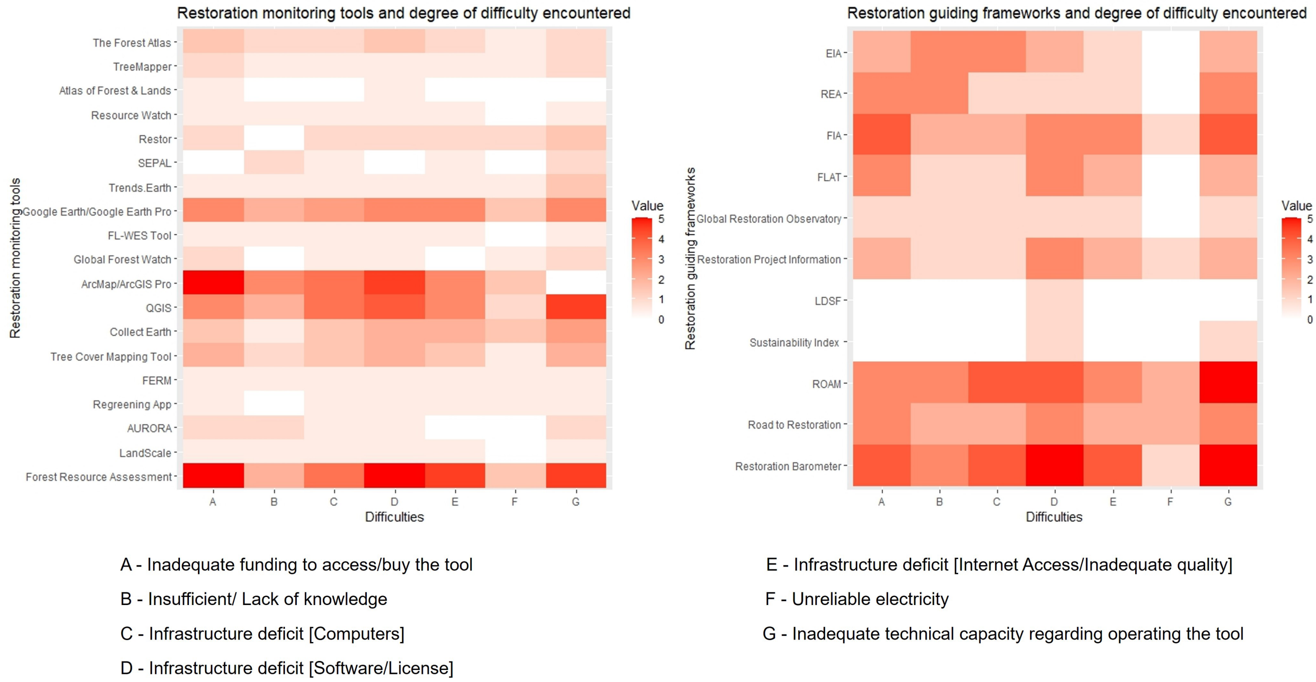

Figure 5. Difficulties encountered when using the restoration monitoring tools/guiding frameworks. EIA, Ecological Integrity Assessment; FIA, Forest Monitoring Program; REA, Rapid Ecological Assessment.

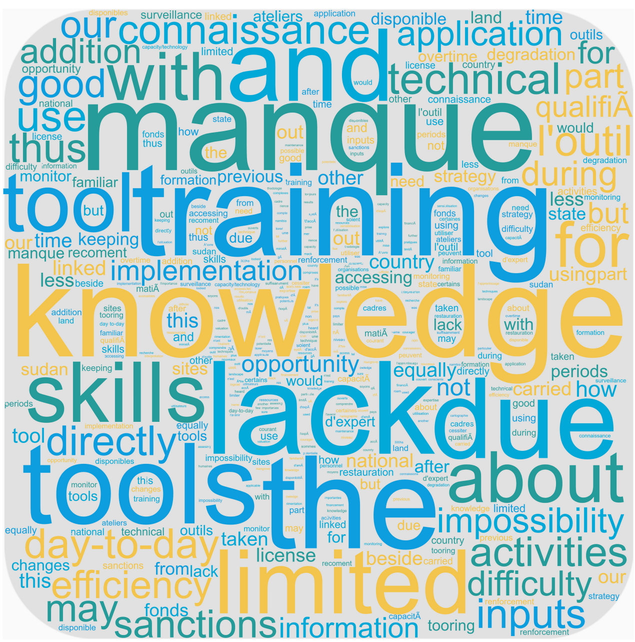

Figure 6. Constraints preventing the use of the restoration monitoring tools/guiding frameworks among the surveyed practitioners.

proportion of socio-economic indicators, followed by biophysical/ecological indicators for capturing progress on restoration. Each of these indicators has metrics for qualitatively and quantitatively measuring their realization. However, there are many more metrics designed to measure biophysical/ecological indicators compared to the other categories of indicators that have a reduced number of metrics. Two justifications can be advanced for this evidence. First, this confirms the observation that focus is mainly put on the tangible and controllable component of restoration interventions because their measurement is easier (Pillay & Buschke 2020; Mansourian & Stephenson 2023), and appropriate metrics have not been developed to assess other categories of indicators. Biophysical/ecological metrics are both remote sensing products and forest cover (gain and loss) metrics, as well as empirical survey-based data. For remote sensing-based metrics, open access to satellite-based products and other general sources/platforms with preprocessed data, such as the GFW, can ease measurements, only if adequate country-level technical capacity exists. Second, this confirms the poor understanding of the social and institutional dimensions of restoration, suggesting the need to pay more attention to those human dimensions of FLR (Mansourian et al. 2024) to enhance the enablers for resilient and sustainable restored landscapes. FLR is an integrated approach that goes beyond ecological to include social, economic, and governance dimensions of restoration, hence the need for a monitoring framework that incorporates these interconnections (Gutierrez et al. 2022). Yet, Chazdon et al. (2021) asserted that because FLR governance is multidimensional and highly contextual, it has been characterized variously in the FLR literature, making it challenging to adequately assign relevant generalizable indicators and metrics. As such, having standard governance and institutional indicators and metrics may be unrealistic (Löfqvist et al. 2023).

Our study showed that most of the indicators developed are top-down. That is, the conceptualization of indicators was not

Table 5. Proposed restoration monitoring instruments from a pragmatic perspective.

Category	*Indicators*	*Metrics*	*Tools/guiding frameworks*
Ecological/ biophysical	Area of land under restoration	Tree density	Framework for Ecosystem Restoration Monitoring (FERM)
		Decline in forest fires in village land forest reserves and community-based forest reserves	
		Tree survival rate	Restoration Barometer
		Forest area restored, reforested, or under improved management (ha)	Road to Restoration Collect Earth
		Area under natural regeneration	Google Earth Pro
		World Conservation Union Red list species planted/ regenerated	QGIS/ArcGIS Global Forest Watch
		Amount of restored area showing an increase in Normalized Difference Vegetation Index (NDVI) and the Land Surface Water Index (LSWI) correcting for short-term climate effects	Tree Cover Mapping Tool Restoration Opportunity Assessment Methodology (ROAM)
		Decrease in intensity of forest loss	LandScale
		Net primary productivity	
	Water quality and quantity	Water stress—proportion of water withdrawn compared to available water resources	
		Percentage in sediment yield	
	Protected area coverage, ecological diversity, and connectivity	Key Biodiversity Area (KBA) targets/protected area coverage	
		Percentage increase in species/abundance of indicator species	
Socio-economic and cultural	Jobs created	No. of women, men, and youth employed through restoration	
		Number of jobs	
		Number of individuals employed	
		Type of job (seasonal, casual, or occasional)	
		Job time frame (short and long)	
	Livelihood and economic benefits from restoration-related activities	No. of non-timber forest products available on a sustainable basis	
		Reduced water use in irrigation	
		No. of female farmers benefiting from an improved agricultural, aquaculture, and forest-based produce.	
		No. of small to medium scales dams developed	
		No. of rainwater harvesting structures developed	
		Length of feeder roads rehabilitated (km)	
		No. of river crossings/rural bridges rehabilitated	
		No. of market shades rehabilitated	
		No. of multiple-use water sources developed	
		Percentage change in household income levels	
		No. of household benefiting from alternative income-generating activities	
	Product harvested	Yields of selected agricultural commodities supported by the project (%)	
		Proportion (%) of target farmers benefiting from an increase in production sold to the markets and/or an increase in income from marketed products	
	Improvements in health and nutrition	No. of households with food security improved	
	Impact of shocks and stresses	Percentage of people affected by climate-related natural disasters over the last 5 years	
		No. of buildings/dwellings affected by natural disasters	
	Clean energy access	Increase in number of households using improved stoves	
	Use of knowledge innovations and practices	Percentage of farmers that use traditional techniques	

Table 5. Continued

Category	*Indicators*	*Metrics*	*Tools/guiding frameworks*
	Agricultural management	Percentage of households within targeted catchments engaged in sustainable land management practices	
	Value of restored ecosystem benefits	Expected annual earnings through ecosystem benefits from floodplains	
Institutional/ governance	Access and rights to land and natural resource tenure	No. of farmers with tenure certificates Ha of land registered Ha of land adjudicated	
	Governance arrangement/ local government arrangement	Institutions annual average performance score (%)	
	Protection and management	Increased protection status Management effectiveness score in most reserves Areas FSC certified (Forest Stewardship Council)	
	Area under local management/co-management	No. of ha managed by community-based organizations Total area of new village land forest reserves	
	New supportive policies	New legislation/by-laws	

participatory and did not consider Indigenous and local knowledge. The values and knowledge systems of Indigenous Peoples and local communities and their practices have been demonstrated to play a substantial role in conservation and restoration (Lake et al. 2018; Reyes-García et al. 2019; Brondízio et al. 2021), but such potential remains largely dismissed in restoration monitoring efforts. Moreover, the indicators mainly focused on quantitative outcomes (Löfqvist et al. 2023), are theoretical, difficult to use, create unrealistic targets, and are costly to implement. This confirms trends in literature that problematize such top-down and non-inclusive approaches. For instance, Méndez-Toribio et al. (2021) highlighted that ecological restoration monitoring usually takes a top-down approach and is mostly focused on short-term indicators. Also, top-down restoration programs usually overlook the importance of local context in designing monitoring instruments (Stanturf & Mansourian 2020). We argue that involving stakeholders at various scales or levels in designing monitoring instruments will enhance their acceptability, legitimacy, and appropriateness as well as inclusivity. Such a process engenders bottom-up monitoring, or participatory monitoring from the ground up (Chazdon et al. 2021; Marshall et al. 2022; Nelson et al. 2024). Noulèkoun et al. (2021) mentioned that due to the dynamic nature of socio-ecological systems, participatory monitoring is needed to maintain momentum over time and adapt instruments to global changes to appropriately capture FLR outcomes. The evaluation of FLR outcomes based on collaboratively designed indicators will ensure that lessons and learnings are integrated for better adaptive management. Involving diverse stakeholders in the design and monitoring of restoration activities may facilitate upscaling and lowering of the cost involved.

Regarding the tools/guiding frameworks, most were designed with the focus of measuring biophysical indicators, such as the area of land under restoration, water quality and quantity, and protected area connectivity, and are also divorced from a bottom-up approach. Existing guiding frameworks tend to focus on a particular dimension of FLR and are not holistic. Yet, the guiding framework, according to Chazdon et al. (2020), consists of criteria and indicators that align with the principles of FLR and must integrate the measurement of ecological, socio-economic, and governance outcomes. Also, there were no monitoring tools dedicated to assessing socio-economic and institutional indicators, confirming Petrosillo et al. (2013) assertion that socio-economic and institutional indicators are challenging because they are multidimensional and often subjective concepts. The authors argue that these concepts are mostly interconnected with each other, unlike biophysical attributes that can be objectively measured.

Further, most existing tools and guiding frameworks for monitoring restoration require extensive knowledge and multi/ interdisciplinary skills to effectively use them. For instance, tools such as Ecological Recovery Wheels require knowledge of ecology, remote sensing, and social dimensions of the environment. Also, to use the SEPAL, one must have the knowledge and skills in geographic information system (GIS), remote sensing, and coding. Therefore, there is a need for extensive targeted training on geospatial technology applications and funding allocated for restoration monitoring while also easing the monitoring complexities with simpler, low-cost, and effective monitoring tools, as Mansourian and Vallauri (2022) put forward.

What Actions Are Needed to Accelerate FLR Monitoring?

The findings on FLR monitoring feasibility point toward several tangible actions to accelerate restoration monitoring, especially in the African development context. First, capacity development is a significant ingredient in advancing and scaling up the progress of FLR monitoring. Monitoring efforts should consider adequate training and capacity building to enhance the skills and expertise needed to ensure that local capabilities meet FLR monitoring needs (Meli et al. 2019). This includes activities geared toward enhancing technical skills and expertise and providing a platform for networking and knowledge exchange. Such action can be catalyzed by capacity development and education under the auspice of the AFR100 flagship—Restoration Academy—(UNEP & FAO 2023), and other supportive parallel efforts such as the Landscape Academy (Global Landscapes Forum 2024), which could expand its focus to integrate monitoring capacities and skills. Training should be designed to align with their specific context, incorporate all the dimensions of FLR, and align with the goals of the restoration project (Bloomfield et al. 2019). In their work, Nelson et al. (2024) emphasized the importance of developing the necessary skills, competencies, and knowledge to achieve the desired outcomes and impact in restoration programs. Therefore, conducting a needs assessment for the restoration program becomes crucial in identifying skill gaps and capacity limitations among stakeholders, particularly implementers. Additionally, it is essential to customize such training to account for variations in languages, cultures, and communication styles.

Second, the findings on the practicability of the tools imply the need for adequate infrastructural development to take place to enable seamless use of such tools, including assuring quality internet connectivity among other infrastructural deficits. The choice of monitoring tools and indicators needs to be influenced by local technical capacity and the availability of funds (Mansourian & Stephenson 2023). Africa still faces technological disparities, which have substantial repercussions across its economy. These disparities stem from inadequate infrastructure, including limited access to the internet, unreliable electricity, and poor equipment in terms of computers and advanced GIS and remote sensing software, hindering technological progress. Most monitoring tools and related add-ons require consistent access to the internet and electricity, which is a challenge in the context of Africa (Stephenson et al. 2021).

Third, the findings also suggest that adequate funding is needed to support FLR monitoring. Findings that some tools may need to be purchased or that their accessibility may require a software license and/or other add-ons suggest that to meet the needed monitoring requirements, restoration projects must plan for the purchase of commercially available software or tools. Landscape restoration is a long-term initiative that requires continuous funding over its lifespan, but the persistent focus on short-term indicators and metrics means that donor funding will be aligned with such objectives (Mansourian & Stephenson 2023). Inadequate financial capital has been singled out as one of the factors limiting the process and upscaling restoration efforts to meet global targets. Similarly, restoration budgets often fail to allocate sufficient funding for monitoring and evaluation. Explicitly incorporating these subcomponents into the restoration plan will aid in creating appropriate budgets. Budgetary flexibility, or the inclusion of discretionary funds, can help accommodate necessary adjustments to restoration activities arising from adaptive management (Nelson et al. 2024). Also, most of the finance for landscape restoration comes from the public purse with limited investment from the private and other sectors of the global economy (Löfqvist & Ghazoul 2019; Löfqvist et al. 2023; zu Ermgassen & Löfqvist 2024). Specifically, private finance mechanisms historically underinvest in monitoring and impact evaluation, favoring cost-effective nature-based solutions like plantation monocultures over naturally regenerated ecosystems (zu Ermgassen & Löfqvist 2024). As such, accelerating restoration and its monitoring requires private financing to complement public funding in all aspects at all scales (Chazdon et al. 2020; Löfqvist et al. 2023; zu Ermgassen & Löfqvist 2024).

Overall, effective FLR monitoring is crucial, yet many existing monitoring instruments do not fully reflect or have an unbalanced focus on the comprehensive biophysical, socio-economic, and governance aspects to monitor. Currently, most of the monitoring instruments have been developed in a top-down approach, thereby lacking a situated and participatory approach in their conceptualization. The significant progress in developing specific metrics and tools for measuring biophysical/ecological aspects does not match that of governance/institutional and socio-economic dimensions. Measuring and quantifying biophysical variables are found easier compared to indicators linked to the human dimensions that are inherently more complex as they involve human behavior, governance structure, and cultural context. Efforts to employ tailored tools and guiding frameworks that offer the potential to measure biophysical, socio-economic, and governance indicators, with relevant metrics, are vital for a holistic understanding of restoration outcomes and impacts. Landscape restoration monitoring instruments that lack robust conceptual grounding and disregard the interdependencies among the various dimensions tend to yield incomplete assessments of progress (Gutierrez et al. 2022). Moreover, the limited awareness and utilization of existing monitoring instruments in the African context call for rethinking approaches to accelerate restoration monitoring efforts, with comprehensive and meaningful training as well as low-cost, effective, and pragmatic restoration monitoring instruments designed in a way to address accessibility, availability, and capabilities within the implementation context. Key identified barriers and constraints include knowledge and skill gaps related to the monitoring instruments, infrastructure capacity deficits, and funding shortages. Therefore, the few substantial ongoing efforts focused on capacity development through training need enhancement.

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Supporting Information

The following information may be found in the online version of this article:

Table S1. Summary of identified restoration monitoring indicators and metrics by their categories.
Table S2. Extended overview of identified restoration monitoring indicators and metrics by their categories.
Table S3. Analysis of restoration monitoring tools and guiding frameworks based on the feasibility principles: full extent.
Supplement S1. Paper version of the online survey—English version.
Supplement S2. Paper version of the online survey—French version.
Supplement S3. Ethical clearance: Penn State Institutional Review Board (IRB) exempt approval for the study.

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