Developing indicators for participatory forest biodiversity monitoring systems in South Sumatra

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HIGHLIGHTS
• The study used a hierarchical characterization approach to create a global pool of biodiversity indicators.
• Stakeholders participated in a workshop to select high-performance and rewarding biodiversity indicators using a framework consisting of multi-tiered filters from the pool.
• Because the selected indicators represent landscape, habitat, and species levels as well as structural, functional, and compositional ecosystem attributes they therefore collectively reflect changes in biodiversity.
• The integrated approach ensures a global-local connection and maintains the essence of a participatory approach.
• Selected high-performance and rewarding indicators have the potential to contribute to multiple national reporting requirements.

SUMMARY
There is often a striking disconnect between communities that create biodiversity frameworks, set targets, and design monitoring systems and those that actually implement them. This study aims to (i) develop an integrated (participatory) approach to contextualize available sets of biodiversity indicators to meet specific stakeholders’ needs, and (ii) select high-performance and rewarding indicators for participatory forest biodiversity monitoring systems (PFBMS). We used a hierarchical characterization approach to biodiversity to create a global pool of indicators. Specialists then used a framework consisting of multi-tiered filters to select high performance and rewarding indicators from the pool applicable to PFBMS at province and forest management unit levels in Indonesia. Selected indicators are able to reflect changes taking place at various levels in the ecological hierarchy from landscape, habitat, to species level including complete ecosystem attributes, i.e., structural, functional, and compositional. The integrated approach combines the expert guidance and experience of professionals at province and local levels; ensures global-local connection; and follows the participatory approach.

Keywords: biodiversity, hierarchical characterization, monitoring, rewarding indicators, Sumatra

Développer des indicateurs pour les systèmes de gestion de la biodiversité de la forêt participative dans le Sumatra du sud

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Une déconnexion frappante existe entre les communautés qui créent des cadres de biodiversité, tracent des buts et conçoivent des systèmes de gestion et ceux qui les mettent en pratique. Cette étude cherche à (i) développer une approche intégrée (participative) pour contextualiser les ensembles disponibles d’indicateurs de biodiversité, afin de pouvoir aux besoins spécifiques des parties prenantes et, (ii) sélectionner des indicateurs fructueux et très performants pour les systèmes de gestion de la biodiversité de la forêt participative (PFBMS). Nous avons adopté une approche de caractérisation hiérarchique de la biodiversité pour créer un ensemble global d’indicateurs. Les spécialistes ont ensuite utilisé un cadre consistant de filtres à plusieurs niveaux, pour sélectionner les indicateurs fructueux et à forte performance des indicateurs de cet ensemble applicables aux PFBMS aux niveaux d’unités de gestion forestière et de province en Indonésie. Les indicateurs sélectionnés sont à même de refléter les changements en cours à divers niveaux de la hiérarchie écologique, du niveau du paysage et de l’habitat, jusqu’à celui des espèces, incluant les attributs d’écosystèmes complets, c.a.d, structurels, fonctionnels et composénnels. L’approche intégrée combine l’orientation experte et l’expérience des professionnels aux niveaux provincial et local, elle assure une connexion du global au local et est fidèle à l’approche participative.
Desarrollo de indicadores para sistemas de monitoreo participativo de la diversidad biológica forestal en el sur de Sumatra

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A menudo existe una desconexión sorprendente entre las comunidades que crean marcos de biodiversidad, establecen objetivos y diseñan sistemas de monitoreo y las que los aplican en la práctica. Este estudio tiene por objeto: i) desarrollar un enfoque integrado (participativo) para contextualizar los conjuntos disponibles de indicadores de la diversidad biológica con el fin de satisfacer las necesidades específicas de los interesados y ii) seleccionar indicadores de alto rendimiento y de gratificación para los Sistemas de Monitoreo Participativo de la Biodiversidad Forestal (SMPBF). Se aplicó un enfoque de caracterización jerárquica de la biodiversidad para crear un conjunto global de indicadores. A continuación, los especialistas utilizaron un marco basado en filtros de varios niveles para seleccionar indicadores de alto rendimiento y de gratificación dentro del conjunto aplicable de SMPBF a nivel de provincia y de unidad de gestión forestal en Indonesia. Los indicadores seleccionados son capaces de reflejar los cambios que se producen en diversos niveles de la jerarquía ecológica, desde el paisaje y el hábitat hasta el nivel de las especies, pasando por la totalidad de los atributos del ecosistema, es decir, estructurales, funcionales y de su composición. El enfoque integrado combina la orientación de los expertos y la experiencia de los profesionales en las escalas provincial y local, a la vez que asegura la conexión entre lo global y lo local y mantiene el enfoque participativo.

INTRODUCTION

Rapid global change poses fundamental challenges to the survival of natural ecosystems and the biodiversity they host (Perino et al. 2019). The unprecedented loss in biodiversity over the last decades has emerged as a global crisis. In its recent assessment of the state of the world’s biodiversity, The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) revealed that on average some 25% of animals and plants are now threatened with extinction (IPBES 2019). Natural ecosystems have declined by 47% on average and a million species1 now face extinction within the third decade of this century. This corresponds to a rate of destruction tens to hundreds of times higher than the average rate over the past 10 million years (IPBES 2019). Biodiversity loss is not only an environmental problem but, like climate change, it also affects sustainable development, human health, food security, water, and energy issues (Sunderland 2011, Oswald Spring 2016, Tidwell 2016, Cramer et al. 2017, Roe et al. 2019). Coupled with this habitat change, rapid climate change has placed biodiversity under unprecedented pressure. Deforestation and tree decline have a direct impact on climate change by increasing the overall carbon emissions and exacerbating anthropogenic climate change (IPCC 2007), on the other hand, pronounced and rapid climate change has a profound impact on biodiversity (Kremer et al. 2014) that may lead to a cycle of tree decline (Sabaté et al. 2002, Bréda et al. 2006). To achieve Sustainable Development Goals (SDGs), the global community needs to confront both problems – climate change and the biodiversity crisis (Roe et al. 2019). There is a growing need to understand the nexus between the multifaceted problems of biodiversity loss and climate change in order to address the imminent “bio-climate catastrophe”2. Climate driven issues such as sea level rise, food shortage, disease spread, and massive biodiversity loss only promise ever worsening effects (Overpeck and Conde 2019). In response, the seventh session of the Plenary of the IPBES (2019) adopted IPBES’s second Rolling Work Program (up to 2030) that includes preparing a technical report on biodiversity and climate change intended to be prepared jointly with the Intergovernmental Panel on Climate Change (IPCC).

In 2010, Parties to the Convention on Biological Diversity (CBD) adopted the Strategic Plan for Biodiversity 2011–2020, and its 20 Aichi Biodiversity Targets, to catalyze national and international conservation efforts and reverse negative biodiversity trends (Visconti et al. 2019). As the strategic plan nears its end, the global community is now developing a post-2020 biodiversity framework3, the adoption of which will be negotiated by the CBD in its fifteenth session of the Conference of the Parties in 2020. The post-2020 biodiversity framework should be aligned with the 2050 Vision for Biodiversity, other biodiversity-related conventions, SDGs, the Paris Agreement, and global initiatives such as forest landscape restoration initiatives. There is often a striking disconnect between the community that develops such a framework and sets the targets, e.g., international groups and national governments, and those who implement the framework to achieve the targets, for example, Forest Management Units (FMUs), Community Forest User Groups (CFUGs) and Indigenous Peoples and Local Communities (IPLCs).

The use of criteria and indicators (C&I) to evaluate the sustainability of forest management has been growing since the Rio de Janeiro Earth Summit in 1992 (Linser et al. 2018). In the third decade of the 21st century, assessment, monitoring,
and reporting on the forest conditions and trends including forest diversity, health, and vitality has grown increasingly important in the context of the alarming bio-climatic crisis, SDGs, the United Nations Forum on Forests (UNFF) Global Forest Goals and post-2020 biodiversity framework. Measures in place to assess biological conditions have not, however, improved over time (Geldmann et al. 2015). Intergovernmental, regional, and international forest-related C&I processes already provide a large amount of C&I. There is obviously no need to reinvent the wheel, nor is a large volume of C&I needed in a single biodiversity monitoring program. However, there is a demand for (i) a framework that sets the available C&I in a relevant local context, (ii) a system for selecting the most functional and flexible indicators that can be used effectively and efficiently, and (iii) enhanced global-local connections to facilitate the implementation of forest biodiversity monitoring. The objective of this research was to implement these three aspects in the development of a set of indicators for a participatory forest biodiversity monitoring system (PFBMS) at local level.

In line with this objective, this study addresses two major issues: (i) developing a participatory approach to contextualize the globally available comprehensive list of biodiversity indicators suitable for the specific stakeholders’ needs, and (ii) selecting the high-performance and rewarding set of indicators which are able to generate a significant amount of ecologically meaningful information on changes in forest condition and biodiversity for a relatively low investment (Gardner 2010). These are the core set of viable and efficient indicators selected from a comprehensive pool of indicators.

A systematic review of literature suggested a large number of indicators for biodiversity monitoring. The indicators were collected in an indicator matrix which was prepared based on the hierarchical characterization approach to biodiversity (Noss 1990), and a global pool of indicators is created. A stakeholder workshop was held in Palembang, South Sumatra, Indonesia. From the pool, workshop participants selected the high-performance and rewarding indicators using a multi-tier framework adapted from Gardner (2010). The approach utilized in this study recognizes the value of the collaborative exercise (Coleman et al. 2019). This study aims to contribute to current literature related to biodiversity indicators and biodiversity monitoring, and to the development of a PFBMS. The PFBMS serves as a valuable and functional institutional structure to achieve a country’s biodiversity targets in line with the Aichi Biodiversity Target and post-2020 biodiversity targets. The participatory approach used in this study to select indicators constitutes a crucial element of the PFBMS.

**Deforestation in Indonesia; causes and consequences**

Since 1990, the world has lost 420 million ha (M ha) of forest through deforestation, and for 2015–2020, the annual rate of deforestation was estimated at 10 M ha. However, the rate of net forest loss declined from 7.8 M ha yr⁻¹ (1990–2000) to 5.2 M ha yr⁻¹ (2000–2010) and 4.7 M ha yr⁻¹ in 2010–2020 (FAO 2020). Asia had the highest net gain in forest area in 2010–2020 with annual forest area net change of 1.2 million ha (FAO 2020). On the contrary, Indonesia exhibited the largest increase in forest loss (0.1 M ha yr⁻¹) with over 2 M ha yr⁻¹ in 2011 to 2012, which was double of that recorded between year 2000 to 2003 (Hansen et al. 2013). Similar trends have been observed by studies using remote sensing with 0.7 M ha and 0.9 M ha annual change in “forest cover” for the periods of 2000–2005 and 2000–2010, respectively (Miettinen et al. 2011, Hansen et al. 2013, Stibig et al. 2014).

Rapidly expanding pulp and palm oil production is the leading factor in accelerated deforestation (Zarin et al. 2016). Countries such as Brazil, Chile, and Indonesia have become global players in the world’s pulp market by making the most of a strategic advantage – climates conducive to fast growth rates (Abramovitz and Mattoon 2000). Palm oil was the highest exported commodity for 2011 in Indonesia, accounting for the 18.97% of the total export and the trend of export is increasing. Indonesia contributed 53% of the global palm-oil production in 2013 (FAO 2015, Gaveau et al. 2016). Between 1982 to 2007, in Riau region alone, these two industries replaced ca. 2 M ha of natural forest (Uryu et al. 2008). Between 2000 and 2012, Indonesia lost 6 M ha of old-growth and selectively logged natural forests (Margono et al. 2014, Gaveau et al. 2016).

Plantation expansion and the timber industry have been heavily subsidized in Indonesia for years (Zarin et al. 2016). Pulp production has quadrupled in the last decade with more than 1.4 M ha of natural forest has been replaced by plantations. The predominant forestry plantation activity is the industrial plantation of acacia species (Acacia mangium and Acacia crassicarpa) and eucalypts (Eucalyptus pellita), primarily for pulpwod plantations with short rotation cycles of 6–7 years (Verchot et al. 2010). The replacement of natural forests either with monoculture palm plantations or with the acacia or eucalypts reduces overall plant diversity and eliminates many animal species that depend on natural forests (Fitzherbert et al. 2008, Vijay et al. 2016). A third of the mangrove cover is gone from Indonesian coasts due to logging and shrimp farming. Pulpwod plantations have also had adverse effects on local people. Plantation programs have even displaced indigenous Dayak communities (Abramovitz and Mattoon 2000).

Indonesia ratified the United Nations Convention on Biological Diversity (CBD) in 1994, two years after signing. The country’s archipelagic geography, geographic location, and tropical climate enable it to support the world’s second highest level of biodiversity. Indonesia’s flora and fauna are a mixture of Asian and Australasian species and the result of its geographic location as a meeting point of Asia and the Australian continent. It hosts some of the most bio-diverse ecosystems on Earth and unique species such as the critically endangered Sumatran tigers and endangered Sumatran elephants (Uryu et al. 2008). However, the rapid conversion of natural forests in Indonesia has had a tremendous effect on biodiversity and has contributed to the decline and extinction of biodiversity worldwide. Eissner et al. (2016) noted that the areas with the highest rates of increased deforestation
are broadly located together with the areas with highest biodiversity threats. The accelerated deforestation together with high biodiversity endemism makes Indonesia the country of the greatest increased threat to biodiversity (Eisner et al. 2016).

**Biodiversity monitoring-context, definition, and objectives**

Biodiversity conservation is one of the goals of ecologically sustainable forestry, although the concept encompasses much more than biodiversity conservation alone. Biodiversity includes life in all its forms, from the level of gene, to species, to complete ecosystem and including all processes of the ecosystem that maintain these various levels (Noss and Cooperrider 1994, Hunter 1996). Given this complexity, it is difficult to judge whether forests/ecosystems are being managed in ecologically responsible ways. Generally, we lack understanding about whether the current forest management plans and processes meet the long-term goal of biodiversity conservation.

Identifying ways to conserve forest biodiversity in different types of forest use (protection and production) and forests under different management (forests managed under FMUs and by the CFUGs and IPLCs) and supporting sustainable management regimes has been a major research priority in recent years (Gardner 2010). Biodiversity conservation in managed forests, secondary/logged over forests and planted forests is gaining considerable attention. If forest loss exceeds plantations, then the focus should be on stopping forest loss. Alternatively, if the management of the plantations can be adapted so that they support a substantial proportion of tree species while maintaining high yields, conservation efforts should focus on ways to enhance biodiversity in plantations (Green et al. 2005, Fitzherbert et al. 2008). Neupane et al. (2017) found that planted forests in Northern Vietnam were composed of 72 species indicating a thriving natural regeneration of native trees in the forest plantations (Neupane 2015).

Biodiversity monitoring is a process of assessing the existing status and change in the condition of biodiversity, as measured against a set of criteria and indicators (ANSAB 2010). The process determines the status and trends of biological diversity executing repeated measurements under continuous observation. Biodiversity monitoring mostly relies on qualitative and quantitative indicators. Biodiversity monitoring programs play a vital role in providing the information needed for conservation purposes and for developing ecologically responsible management strategies that enhance opportunities for conservation. The general objectives of biodiversity monitoring are to i) promote sustainable forest/biodiversity management by providing tools, methods and techniques needed to generate monitoring data, ii) assess the impacts of forest management activities on biodiversity and health of forest ecosystem, and iii) support the development of a baseline measurement of biodiversity that make it possible to monitor changes to the resource base.

**Challenges to developing biodiversity indicators**

Biodiversity is a broad concept to measure in its entirety. Generally, in tropical forests there are thousands of flora and fauna species and countless possible species interactions hence making it impossible to measure them completely. In nature, no two forest systems are identical, each is unique in its components and processes. Therefore, in order to take accurate measurements, the biodiversity in the forest systems needs to be redefined in terms of measurable attributes relevant to the scale and purpose for which it is to be assessed (Sarkar and Margules 2002, Williams 2004, McElhinny et al. 2005). Indicators are usually measurable surrogates that allow isolation of the key aspects of a system from an overwhelming array of signals to describe and monitor biodiversity. Different C&I can be selected differently for different goals. For instance, if the goal is species conservation, focus will be on rare and threatened species while the most common species, even in a derogatory stage, are considered of little interest.

Though the concept and development of a biodiversity indicator is not new, it has recently gained momentum. More than two decades ago Noss (1990) developed a biodiversity indicator matrix that is viewed as instrumental. After the Rio Earth Submit in 1992, rapid international and regional initiatives in C&I processes took place. Subsequently, C&I mechanism emerged as a key mechanism to monitor principles of sustainability in terms of measurable goals. The popularity of the C&I is reflected in the participation of 150 countries, representing 97.5% of the world’s forest area, in one of the nine major ongoing international and regional C&I initiatives and processes (Wijewardana 2008). However, not many of the processes are able to show satisfactory commitment towards SFM and particularly to biodiversity conservation, with a markedly poor showing in tropical countries. Among these, the International Tropical Timber Organization (ITTO) C&I process, Pan-European Process (1993) (Helsinki process, MCPFP) and the Montreal process have a track record of actually putting the theoretical concepts into practice (Wijewardana 2008). Development of C&I has proved to be a powerful information tool that provides a holistic picture representing all major forest values including biodiversity conservation.

Despite the large number of studies, membership in the global initiatives and implementation at the FMU level is rather weak (Raison et al. 2001). There is an immense volume of literature on biodiversity indicators (Ferris and Humphrey 1999, Poiani et al. 2000, Hagan and Whitman 2006), but there is no single literature that can identify a single coherent framework (Lindemann et al. 2000, McElhinny et al. 2005). This literature has, however, made clear that there is no single indicator that can provide a satisfactory reflection of biodiversity change (Gardner 2010). This could be due to the lack of an applicable framework, or due to the complexity of biodiversity terminology. Many studies about indicators are focused instead on one indicator or indicators concerning individual species and species groups (reviewed in Gao et al. 2015). When such indicators are designed, question remains
whether these indicator sets are sufficient to achieve the goal of developing efficient monitoring of biodiversity and biodiversity conservation as a whole and simple enough to implement with the available human capacity and financial resources (Danielsen et al. 2000).

Promoting and maintaining biodiversity are primary goals of sustainable forestry (Hagan and Whitman 2006). So far, developed C&I mostly focused on implementation and effectiveness monitoring to assess whether the forest management practices comply to agreed standards and satisfy the forest management goals. Even though management interventions are performed according to agreed standards and the results are achieved as per the goals, management practices might still impose detrimental impacts on forest biodiversity. Therefore, the indicators and biodiversity monitoring systems need to evaluate and must provide information on which management practices have beneficial impacts and which are successful in achieving the biodiversity goals. Modified forests lack natural ecological analogue, so the studies of such forests will poorly reflect the ecological dynamics and composition of the undisturbed forest (Hobbs et al. 2006, Gardner 2010). Before and after intervention scenarios could depict the contribution of particular management interventions on biological diversity. However, there is little information available on the baselines (such as baseline data before the human-related impacts) and even if they are available, it would be difficult to differentiate how much of these changes are associated with human related impacts and natural processes (Allen et al. 2003). Thus, developing a clear understanding of the links between a particular management regime and its impacts and changes in biodiversity/ecological integrity via measurable changes in major attributes of the ecosystem/forest provides the foundation for reliably assessing and evaluating management performance (Gardner 2010).

MATERIALS AND METHODS

A hierarchical characterization approach to biodiversity was used as a conceptual framework for identifying specific, measurable indicators to monitor change and assess the overall status of biodiversity (Noss 1990). The approach includes all three major attributes of the ecosystem, i.e. the function, composition, and structure at four levels of organization: regional-landscape, community-ecosystem, population-species, and genetic (Noss 1990) (Supplementary Materials, Figure 1). Function involves ecological and evolutionary processes including gene flow, disturbances, and nutrient cycling. Many approaches to biodiversity monitoring often ignore ecological processes (e.g. natural disturbance, decomposition of woody debris, cycling of nutrients, etc.) that are critical for the maintenance of biodiversity (Noss 1990). However, this ignorance fails to provide a complete definition of biodiversity. Composition refers to the identity and variety of elements in a collection that include richness and abundance. It is commonly measured by counting the number of plant and animal species present in a given area (Ferris and Humphrey 1999). Structure attributes of the biodiversity involve physical organization or pattern of a system from habitat complexity, as measured within stand communities, to the pattern and other elements at the landscape level.

The structural, functional, and compositional attributes of a stand are often interdependent and interconnected, so that attributes from one group may also be surrogates for attributes from another group (Noss 1990, Ferris and Humphrey 1999, Franklin et al. 2002, McElhinny et al. 2005). For example, a structural attribute such as dead wood can also be a good indicator of functional attributes such as decomposition and nutrient cycling processes (McElhinny et al. 2005). Similarly, compositional attributes, such as species composition and abundance can be indicators of structural attributes such as canopy layering (Franklin et al. 2002, Gardner 2010). Furthermore, measures from one scale can provide information relevant to another scale (Olsen et al. 2007, Lin et al. 2009).

Collection and categorization of biodiversity elements related to forest ecosystems

For this study we created an indicator selection matrix based on different organizational levels: (i) landscape level, (ii) habitat/ecosystem level, (iii) population/species level, and (iv) genetic level. Each level was further arranged into three categories/attributes of biodiversity: (i) composition, (ii) structure, and (iii) function. Once the matrix was completed, we used the ISI Web of Knowledge to review literature using combinations of different keywords: “biodiversity monitoring”, “indicator selection”, “indicator”, “biodiversity”, and “forests”. The search was restricted to only peer reviewed literature and books. Studies, publications, and reports at the regional and broader scale (e.g. ITTO, CIFOR, CBD) were also included in the study. The literature and studies all clearly involved biodiversity or ecological indicators.

A rapid review of the abstracts of the retrieved 562 peer reviewed articles was conducted, and 52 relevant articles were screened. A seminal study conducted by Prasetyo et al. (2014) in South Sumatra provided a valuable reference to prepare the indicator matrix. Out of the 52 articles, 17 of the most relevant papers dealing with biodiversity indicators were selected. Since many studies were based on only one or only a few attributes (e.g. structural indicators only), and at limited spatial scale (e.g. literature involved with population level studies only), we considered four criteria to characterize and assign each indicator described in the literature to a particular category: purpose of indicator (e.g. habitat quality assessment, ecological status assessment), indicator type, spatial scale, and biodiversity attributes addressed. Each selected indicator was added as an entry to our pool of indicators. One important caveat of this work is that the set of keywords used for the literature survey might have influenced our indicator list.

Indicator ranking/screening

Once the indicator matrix with indicators was completed, we used it to select and rank the potential set of indicators that are relevant to the South Sumatra province at FMU level. We then
held a two-day workshop in Palembang involving thirty experts (i.e. decision makers, academics and researchers, and professionals working in the field of forest and biodiversity management with knowledge of some components of biodiversity in different temporal and spatial scales). The experts were tasked with ranking the importance of indicators for the three levels of biological organization (landscape level, ecosystem/habitat level and population-species/stand level) as well as for the three ecosystem attributes: composition, structure, and function. In the first stage, each expert was provided with 10 stickers and requested to rank indicators based on his/her personal importance preference. Experts were able to assign more than one sticker to each indicator, based on the weightage given to indicators.

In the second stage of the workshop, the 30 participants were allocated to three expert groups on the basis of the organizations/institutes they were representing. Group I included 13 experts representing FMUs, forestry concessions and other

**FIGURE 1** A general framework for selecting highly rewarding indicators for the biodiversity monitoring (Source: Adapted from Gardner, 2010)
field-level forestry professionals (FMU expert panel), group II included 12 experts representing government agencies, i.e. decision makers for the National Parks, Climate Change and Fire Prevention Agency, Natural Resource Conservation Agency, Forestry Agency of South Sumatra, Planning and Developing Agency of South Sumatra (Government expert panel), and group III composed of five experts representing academia (universities) and research agencies (Academia expert panel). Each group was provided with the initial set of indicators and parameters (Supplementary Materials, Table 1) created through the literature review. Experts were asked to select/prioritize indicators that are useful and relevant, (i) to the province level, and (ii) to the FMU level forest biodiversity monitoring. The screening of the indicator was primarily based on the ultimate objective of biodiversity conservation. Participants of the workshop decided that the C&I developed at the genetic level should be excluded in the selection process. The major reasons for the exclusion were the lack of expertise and prior experience of and limited or absence of knowledge on the functional importance of the indicators among the field-level forest management practitioners.

Selection of high-performance and rewarding indicators for forest management units

Once the set of indicators relevant to the FMU level were identified, filters (Fig. 1) were applied to select high-performance and rewarding indicators as proposed by (Gardner 2010). The indicator selection processes proved effective as an assessment tool, and as suggested by Gardner (2010) we proceeded using four selection criteria, namely: (i) the ‘responsiveness’ of candidate indicators to management actions, (ii) the ease with which they can be measured, (iii) their relevance to changes in the forest condition and biodiversity and/or individual target species, and (iv) the generality with which they can be applied across similar management systems in other landscapes and regions. The process considered all of these principles and used them as filters at different stages of the selection process.

RESULTS

Initial set of indicators (‘Global pool’ or ‘Laundry list’)

The literature review generated altogether 62 indicators and 162 parameters/variables. A compilation of biodiversity indicators is presented in Table 1 and the parameters/variables are given in supplementary material. The indicators are organized into four hierarchical levels: landscape, habitat, species, and genetic levels. Each level includes all three ecosystem attributes, i.e., structural, functional, and compositional attributes. As with most of the categorization process, there is an overlap between the indicators at different levels.

Preference ranking of the indicators

The most preferred biodiversity indicators from the first stage of the selection process, in which individual experts ranked each indicator (as indicated by the number of stickers the experts assigned to the indicators), are (in descending order): species diversity (18), forest and/or forest land restoration (15), forest carbon stock (14), invasive species (threats) (13), species richness (11), effect of climate change (11), habitat suitability (11), land use types (7), habitat features (7), land cover types (6), ecosystem/habitat/pattern types (6), productivity and resilience (6), population dynamics (6), keystone species (5) and connectivity (3). Within the top fifteen, interestingly, nearly equal numbers of indicators were associated with the three biological organization levels, and the three biodiversity attributes (Table 1).

Candidate forest biodiversity indicators relevant to South Sumatra province

Fifty-six indicators out of 58 (after excluding indicators developed at genetic level) were collectively selected by the expert panels (Table 1) for the province-level forest biodiversity monitoring system. The Academia expert panel selected the highest number of indicators (48 indicators out of 58). The Government expert panel selected 33 indicators, while the FMU expert panel chose 31 indicators (Table 2).

For the province level, 18 indicators (~ 31%) received common agreement among the three expert panels. Those indicators included: land cover types, ecosystem/habitat/pattern types, land cover (area, proportion), landscape fragmentation, transportation effect, forest carbon stock, successional stage, effect of climate change, species diversity, forest condition, forest and/or forest land restoration, keystone species, disturbances, productivity and resilience, species richness, edaphic factors, effect of abiotic factors, effect of abiotic disturbances and population dynamics (Table 1). An additional 20 indicators (~ 34.5%) were thought relevant for the province level by at least two expert panels. The remaining indicators were selected by one of the expert panels (Figure 2). The results show that nearly two-thirds of the total forest biodiversity indicators presented in Table 1 were considered candidate indicators by at least two expert panels.

Candidate forest biodiversity indicators relevant to forest management units (FMUs)

The FMU expert panel selected the highest number of indicators (29 from the list of 58 indicators) relevant to the FMU level biodiversity monitoring system. The Academia expert panel and Government expert panel selected 18 and 13 indicators, respectively (Table 2). The Academia expert panel and Government expert panel selected considerably fewer indicators compared to the FMU expert panel, and compared to the number of indicators they selected for province-level biodiversity monitoring. For the FMU level, 16 indicators (~ 28%) received agreement from at least two expert panels. Those indicators include forest/land restoration, forest carbon stock, threats (invasive species), effect of climate change, species richness (landscape level and ecosystem/habitat
**TABLE 1**  
Forest biodiversity monitoring indicators for inventorying, monitoring, and assessing forest biodiversity. The indicators and variables are presented at four levels of organization, and each level includes compositional, structural and functional components of an ecosystem. The Table presents ranking of indicators by experts participated in the workshop. Selected indicators by different expert groups for the Sumatra Province and Forest Management Unit are represented with the symbol assigned to each expert panel.

(★ = selected by the FMU expert panel, ● = selected by the Academia expert panel, ♦ = selected by the government expert panel)*

| Level of biological organization | Biodiversity (Ecosystem) attributes | Indicators | Ranking of indicators | Indicator selected by three expert panels for Sumatra | Indicator selected by three expert panels for FMU |
|----------------------------------|------------------------------------|------------|-----------------------|------------------------------------------------------|--------------------------------------------------|
| **Landscape level**              | **Composition**                    | Land cover types (e.g., types) | 6 ★● ●                          | ★ ● ●                                                | ★ ● ●                                            |
|                                  |                                    | Species richness               | 10 ●                                  | ● ● ●                                                | ● ● ●                                            |
|                                  |                                    | Ecosystem/Habitat type/Patch types | 6 ★● ●                                 | ★ ● ●                                                | ★ ● ●                                            |
| **Structure**                    |                                    | Land cover types (area, proportion) | 3 ★● ●                               | ★ ● ●                                                | ★ ● ●                                            |
|                                  |                                    | Ecosystem/Habitat type          | 1 ●                                  | ● ● ●                                                | ● ● ●                                            |
|                                  |                                    | Land use types                  | 7 ● ● ●                              | ● ● ●                                                | ● ● ●                                            |
|                                  |                                    | Landscape shape                 | 2 ★                                  | ● ● ●                                                | ● ● ●                                            |
|                                  |                                    | Connectivity                    | 3 ★● ●                              | ★ ● ●                                                | ★ ● ●                                            |
|                                  |                                    | Degree of isolation             | 0 ● ● ●                              | ● ● ●                                                | ● ● ●                                            |
|                                  |                                    | Landscape fragmentation         | 3 ★● ●                              | ★ ● ●                                                | ★ ● ●                                            |
|                                  |                                    | Transportation effect           | 0 ★● ●                              | ★ ● ●                                                | ★ ● ●                                            |
|                                  |                                    | Silvicultural operations        | 0 ●                                  | ● ● ●                                                | ● ● ●                                            |
| **Function**                     |                                    | Forest carbon stock             | 14 ★● ●                             | ★ ● ●                                                | ★ ● ●                                            |
|                                  |                                    | Nutrient cycling                | 0 ★                                  | ★ ● ●                                                | ★ ● ●                                            |
|                                  |                                    | Successional stage              | 0 ★● ●                              | ★ ● ●                                                | ★ ● ●                                            |
|                                  |                                    | Effect of abiotic disturbances  | 0 ★● ●                              | ★ ● ●                                                | ★ ● ●                                            |
|                                  |                                    | Effect of biotic disturbances   | 0 ●                                  | ● ● ●                                                | ● ● ●                                            |
|                                  |                                    | Effect of climate change        | 11 ★● ●                             | ★ ● ●                                                | ★ ● ●                                            |
| **Ecosystem/Habitat**            | **Composition**                    | Species diversity               | 18 ★● ●                             | ★ ● ●                                                | ★ ● ●                                            |
|                                  |                                    | Ecological processes            | 0                                    |                                                      |                                                    |
|                                  | **Structure**                      | Forest types                    | 1 ● ● ●                              | ★ ● ●                                                | ★ ● ●                                            |
|                                  |                                    | Forest condition                | 1 ★● ●                              | ★ ● ●                                                | ★ ● ●                                            |
|                                  |                                    | Forest area in compliance schemes | 0 ●                                  | ● ● ●                                                | ● ● ●                                            |
|                                  |                                    | Forest/land restoration         | 15 ★● ●                             | ★ ● ●                                                | ★ ● ●                                            |
|                                  |                                    | Species distribution            | 1 ● ● ●                              | ★ ● ●                                                | ★ ● ●                                            |
|                                  |                                    | Climatic factors                | 0 ★● ●                              | ★ ● ●                                                | ★ ● ●                                            |
|                                  |                                    | Edaphic factors                 | 0 ● ● ●                              | ★ ● ●                                                | ★ ● ●                                            |
|                                  |                                    | Topographic factors             | 0 ● ● ●                              | ★ ● ●                                                | ★ ● ●                                            |
|                                  |                                    | Structural canopy/elements      | 0 ● ● ●                              | ★ ● ●                                                | ★ ● ●                                            |
|                                  |                                    | Habitat features                | 7 ● ● ●                              | ● ● ●                                                | ● ● ●                                            |
| **Function**                     |                                    | Keystone species                | 5 ★● ●                              | ★ ● ●                                                | ★ ● ●                                            |
|                                  |                                    | Gene flow                       | 0                                    |                                                      |                                                    |
|                                  |                                    | Disturbances                    | 2 ★● ●                              | ★ ● ●                                                | ★ ● ●                                            |
|                                  |                                    | Productivity and resilience     | 6 ★● ●                              | ★ ● ●                                                | ★ ● ●                                            |
| Level of biological organization | Biodiversity (Ecosystem) attributes | Indicators | Ranking of indicators | Indicator selected by three expert panels for Sumatra | Indicator selected by three expert panels for FMU |
|----------------------------------|-------------------------------------|------------|-----------------------|------------------------------------------------------|--------------------------------------------------|
| Population-Species/stand level   | Composition                         | Species richness | 11                   | ★ ● ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ ● ★ 

**Notes:**

*FMU panel- included 13 experts representing FMUs, forestry concessions and other field level forestry professionals in implementing level; Government panel- included 12 experts representing government agencies (decision makers; National Parks, Climate Change and Fire Prevention Agency, Natural Resource Conservation Agency, Forestry Agency of South Sumatra, Planning and Developing Agency of South Sumatra); and Academia panel- was composed of five experts representing academia (Universities) and research agencies.

**Involved workshop participants dropped the genetic level indicators as the local experts lack the genetic expertise and the cost associated with genetic level studies. Therefore, genetic level indicators were removed from table and were not discussed in details.
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level), land use types, land cover types (e.g., types), keystone species, land cover types (area, proportion), landscape fragmentation, forest types, forest condition, tree height, tree dbh, and stand growing stock.

Selection of high-performance and rewarding indicators for FMU level forest biodiversity monitoring systems

After applying the initial filter (availability of necessary field expertise, laboratory expertise, and proven sampling techniques), primary filter (indicator responsiveness, and cost efficiency), and secondary filter (relevance to biodiversity conservation goals, and generality to application) (Figure 1), collectively, 40 indicators were selected as highly rewarding/high performance indicators (Table 3, Figure 3) for FMU level forest biodiversity monitoring. Out of the 40 indicators, four indicators were common to all of the expert panels. Land cover types, land use types, forestland restoration, and species richness (population species/stand level) were the four highly emphasized indicators. Those indicators were also highly preferred (among the top 10) during the preference ranking (Table 1).

There were an additional 12 indicators common to at least two expert panels. They include species richness (landscape level), keystone species, landscape fragmentation, effect of climate change, land cover types (area, proportion), forest carbon stock, forest types, forest condition, invasive species, tree height, tree dbh and stand stock. Remaining indicators were selected by at least one of the panels (Figure 4). The FMU expert panel selected the highest number of indicators (29 from the list of 58, i.e., 50% of the total forest biodiversity indicators presented in Table 1) as high-performance and rewarding indicators applicable to FMU level forest biodiversity monitoring. Moreover, the FMU expert panel classified the selected indicators into two categories, (i) indicators that can be monitored using the existing FMU financial and technical capabilities, henceforth named “unconditional indicators”, and (ii) indicators that can be monitored only with external support, henceforth named “conditional indicators”. The unconditional indicators selected by the experts were land cover types, land cover (area, proportion), land use types, forest carbon stock, species diversity, topographic factors, species richness, invasive species, tree height, tree dbh, stand stock, tree spacing, understorey vegetation, forest product harvest, population structure, edaphic factors, topographic factors, and population dynamics.

FMUs manage forest resources at the local level and provide the basis for improved forest governance, planning, monitoring forest resources, and stakeholder engagement. To strengthen Indonesia’s forest governance and management at the site level, the implementation of 629 FMUs across Indonesia was envisaged by 2019. However, the national FMU roll-out faced substantial budget and staff restrictions. The FMU expert panel pointed out that the FMUs’ existing financial/technical capacities are limited and insufficient for monitoring 10 out of 29 indicators (i.e., conditional indicators) and thus external support is needed. The indicators included species richness, forest types, forest condition, forest/forest land restoration, species distribution, climatic factors, edaphic factors, keystone species, growing stock and genetic diversity. However, the FMU expert panel suggested that the external support needed could be obtained from the existing institutions (academics, governments, non-governmental organizations) already working on the forest management and biodiversity sectors in the province.

TABLE 2 Number of biodiversity indicators selected by the expert panels relevant to Sumatra Province and Forest Management Unit level forest biodiversity monitoring. The ‘laundry list’ (initial set of indicators) contained 62 indicators of which four indicators at genetic levels were not considered in the selection process.

| Level of forest biodiversity monitoring | Academia panel | Government panel | FMU panel |
|----------------------------------------|----------------|------------------|-----------|
| Sumatra Province                       | 48             | 33               | 31        |
| Forest Management Unit                 | 18             | 13               | 29        |

FIGURE 2 Quantity of indicators (percent of collectively selected indicators) relevant to province (South Sumatra) level forest biodiversity monitoring system selected by different combinations of expert panel. F = Expert panel constituting the representatives from forest management units (FMUs), forestry concessions and other field level forestry professionals; A = Expert panel constituting the representatives from academics (i.e., Universities) and research institutes; and G = Expert panel constituting the representative from government agencies (mostly decision making level)
TABLE 3  List of highly rewarding/high-performance Forest Biodiversity Monitoring Indicators (FBMI) applicable to forest management units (FMUs) selected by the experts panels. Rewarding indicators were selected by applying initial, primary and secondary filter (as described in Figure 1)

| Level of biological organization | Biodiversity (Ecosystem) attributes | Indicator | FBMI selected by the academicians and researchers | FBMI selected by the government agencies | FBMI selected by the FMU experts | Rewarding/high-performance indicators (Collective) |
|---------------------------------|-------------------------------------|-----------|-----------------------------------------------|--------------------------------|---------------------------------|-----------------------------------------------|
| Landscape level                 | Composition                         | Land cover types (e.g., types) | ★ ★ ★ | ★ ★ ★ | ★ ★ ★ | ✔ |
|                                 |                                     | Species richness               | ★ ★ ★ | ★ ★ ★ | ★ ★ ★ | ✔ |
|                                 |                                     | Ecosystem/Habitat type/Patch types | ★ ★ ★ | ★ ★ ★ | ★ ★ ★ | ✔ |
| Structure                       |                                     | Land cover types (area, proportion) | ★ ★ ★ | ★ ★ ★ | ★ ★ ★ | ✔ |
|                                 |                                     | Ecosystem/Habitat type          | ★ ★ ★ | ★ ★ ★ | ★ ★ ★ | ✔ |
|                                 |                                     | Land use types                  | ★ ★ ★ | ★ ★ ★ | ★ ★ ★ | ✔ |
|                                 |                                     | Landscape shape                 | ★ ★ ★ | ★ ★ ★ | ★ ★ ★ | ✔ |
|                                 |                                     | Connectivity                    | ★ ★ ★ | ★ ★ ★ | ★ ★ ★ | ✔ |
|                                 |                                     | Degree of isolation             | ★ ★ ★ | ★ ★ ★ | ★ ★ ★ | ✔ |
|                                 |                                     | Landscape fragmentation         | ★ ★ ★ | ★ ★ ★ | ★ ★ ★ | ✔ |
|                                 |                                     | Transportation effect            | ★ ★ ★ | ★ ★ ★ | ★ ★ ★ | ✔ |
|                                 |                                     | Silvicultural operations        | ★ ★ ★ | ★ ★ ★ | ★ ★ ★ | ✔ |
| Function                        |                                     | Forest carbon stock             | ★ ★ ★ | ★ ★ ★ | ★ ★ ★ | ✔ |
|                                 |                                     | Nutrient cycling                | ★ ★ ★ | ★ ★ ★ | ★ ★ ★ | ✔ |
|                                 |                                     | Successional stage              | ★ ★ ★ | ★ ★ ★ | ★ ★ ★ | ✔ |
|                                 |                                     | Effect of abiotic disturbances  | ★ ★ ★ | ★ ★ ★ | ★ ★ ★ | ✔ |
|                                 |                                     | Effect of biotic disturbances   | ★ ★ ★ | ★ ★ ★ | ★ ★ ★ | ✔ |
|                                 |                                     | Effect of climate change        | ★ ★ ★ | ★ ★ ★ | ★ ★ ★ | ✔ |
| Ecosystem/Habitat level         | Composition                         | Species diversity              | ★ ★ ★ | ★ ★ ★ | ★ ★ ★ | ✔ |
|                                 |                                     | Ecological processes            | ★ ★ ★ | ★ ★ ★ | ★ ★ ★ | ✔ |
|                                 | Structure                           | Forest types                   | ★ ★ ★ | ★ ★ ★ | ★ ★ ★ | ✔ |
|                                 |                                     | Forest condition                | ★ ★ ★ | ★ ★ ★ | ★ ★ ★ | ✔ |
|                                 |                                     | Forest area in compliance schemes | ★ ★ ★ | ★ ★ ★ | ★ ★ ★ | ✔ |
|                                 |                                     | Forest/land restoration         | ★ ★ ★ | ★ ★ ★ | ★ ★ ★ | ✔ |
### TABLE 3  Continued

| Level of biological organization | Biodiversity (Ecosystem) attributes | Indicator | FBMI selected by the academicians and researchers | FBMI selected by the government agencies | FBMI selected by the FMU experts | Rewarding/high-performance indicators (Collective) |
|----------------------------------|-------------------------------------|-----------|--------------------------------------------------|----------------------------------------|-----------------------------------|--------------------------------------------------|
|                                  |                                     |           | Initial filter\(^1\) Primary filter\(^2\) Secondary filter\(^3\) | Initial filter\(^1\) Primary filter\(^2\) Secondary filter\(^3\) | Initial filter\(^1\) Primary filter\(^2\) Secondary filter\(^3\) |                                                   |
| Species distribution             |                                     | ● ●       | ●                                  | ●                                      | ★ ★ ★                             |                                                   |
| Climatic factors                 |                                     | ● ●       |                                     | ●                                      | ★ ★ ★                             |                                                   |
| Edaphic factors                  |                                     | ●         |                                     | ●                                      | ★ ★ ★                             |                                                   |
| Topographic factors              |                                     | ●         |                                     | ●                                      | ★ ★ ★                             |                                                   |
| Structural canopy/elements       |                                     | ●         |                                     | ●                                      | ★                                 |                                                   |
| Habitat features                 |                                     | ● ● ●     |                                     | ●                                      | ★                                 |                                                   |
| Function                         |                                     | ● ●       |                                     | ●                                      | ★ ★ ★                             |                                                   |
| Species richness                 |                                     | ● ● ●     |                                     | ●                                      | ★ ★ ★                             |                                                   |
| Growing stock                    |                                     | ● ●       |                                     | ●                                      | ★ ★ ★                             |                                                   |
| Threats (Invasive species)       |                                     | ● ● ●     |                                     | ●                                      | ★ ★ ★                             |                                                   |
| Major structural canopy          |                                     | ●         |                                     | ●                                      | ★ ★ ★                             |                                                   |
| Tree height                       |                                     | ● ● ●     |                                     | ●                                      | ★ ★ ★                             |                                                   |
| Tree dbh                         |                                     | ● ● ●     |                                     | ●                                      | ★ ★ ★                             |                                                   |
| Stand stock                      |                                     | ● ● ●     |                                     | ●                                      | ★ ★ ★                             |                                                   |
| Tree spacing                     |                                     | ●         |                                     | ●                                      | ★ ★ ★                             |                                                   |
| Understory vegetation            |                                     | ●         |                                     | ●                                      | ★ ★ ★                             |                                                   |
| Forest product harvest           |                                     | ●         |                                     | ●                                      | ★ ★ ★                             |                                                   |
| Population structure             |                                     |           |                                     | ●                                      | ★ ★ ★                             |                                                   |
| Morphological variability        |                                     |           |                                     | ●                                      | ★ ★ ★                             |                                                   |
| Edaphic factors                  |                                     | ● ●       |                                     | ●                                      | ★ ★ ★                             |                                                   |
| Topographic factors              |                                     | ●         |                                     | ●                                      | ★ ★ ★                             |                                                   |
| Deadwood stock                   |                                     | ● ●       |                                     | ●                                      | ★                                 |                                                   |
| Habitat suitability              |                                     | ● ● ●     |                                     | ●                                      | ★ ★ ★                             |                                                   |
| Threats (Invasive species)       |                                     | ● ● ●     |                                     | ●                                      | ★ ★ ★                             |                                                   |
TABLE 3 Continued

| Level of biological organization | Biodiversity (Ecosystem) attributes | Indicator | FBMI selected by the academicians and researchers | FBMI selected by the government agencies | FBMI selected by the FMU experts | Rewarding/high-performance indicators (Collective) |
|----------------------------------|-------------------------------------|----------|-----------------------------------------------|------------------------------------------|----------------------------------|-----------------------------------------------|
|                                  |                                     |          | Initial filter<sup>1</sup> Primary Secondary filter<sup>2</sup> | Initial filter<sup>1</sup> Primary Secondary filter<sup>3</sup> | Initial filter<sup>1</sup> Primary Secondary filter<sup>3</sup> |                                  |
| Function                         | Demographic processes                | ●        | ●                                              |                                          |                                  |                                  |
|                                  | Effect of abiotic disturbances       | ●        | ●                                              | ●                                        | ●                                | ●                              |
|                                  | Population dynamics                  |          | ●                                              | ●                                        | ●                                | ●                              |
|                                  | Genetic diversity                    |          | ●                                              | ●                                        | ●                                | ●                              |
|                                  | Effect of biotic disturbances        |          | ●                                              | ●                                        | ●                                | ●                              |
|                                  | Population dynamics                  |          | ●                                              | ●                                        | ●                                | ●                              |
|                                  | Forest resilience                    |          | ●                                              | ●                                        | ●                                | ●                              |

<sup>1</sup> Initial filter = Indicator viability (Availability of necessary field expertise, laboratory expertise, and proven sampling techniques)
<sup>2</sup> Primary filter = Cost effectiveness (Indicator responsiveness, and cost efficiency)
<sup>3</sup> Secondary filter = Relevance to biodiversity conservation goals, and generality to application

DISCUSSION

Selection of preferred indicators reflects the multidimensional ‘metaconcept’

In the study, preference ranking of the indicators from the initial set of indicators shows a nearly equal number of indicators from all three hierarchical levels. Interestingly, such selected indicators are able to reflect changes taking place at various levels in the ecological hierarchy; from population-species, to ecosystem, to landscape level and including all three processes of the ecosystems: structure, composition, and function. This process reflects the importance of the species, habitats, and ecosystems proposed by Noss (1990).

Most biodiversity monitoring studies are based on species diversity only (Spangenberg 2007), or focused on one indicator or indicators concerning individual species and species groups (reviewed in Gao et al. 2015). The species diversity is at the best a very rough indicator of biodiversity. Furthermore, this study argues that accounting for the species’ survival alone is not sufficient to ensure biodiversity.

The engagement of diverse stakeholders, including decision makers, scientists, and local stakeholders, promotes the development of a participatory and scientifically rigorous forest biodiversity monitoring system. The engagement of local actors who actually implement the system is key to developing a participatory and scientifically rigorous system. The selection of the high-performance biodiversity indicators at the province level shows a similar level of understanding between the different groups of experts, as evident by the selection of more than two thirds of common indicators. As mentioned above; these indicators represent each of the three hierarchical levels, as well as diverse stakeholders and an integrated approach which are key to developing a participatory and scientifically rigorous system.
Developing indicators for participatory forest biodiversity monitoring in South Sumatra

FIGURE 3  Schematic overview of the proposed high-performance and rewarding biodiversity indicators applicable to participatory forest biodiversity monitoring system (PFBMS) at forest management units (FMUs). The indicators are shown in a hierarchical characterization approach of biodiversity which includes three major attributes of the ecosystem: structure, composition and function at three levels of organization: landscape level (lime colour-outer circle), community-ecosystem level (orange colour, middle circle) and population-species level (forest colour-inner circle). Genetic level indicators were not discussed in the stakeholder workshop.

initiatives (e.g. Bonn Challenge, New York Forest Declaration), SDGs, UNFF Global Forest Goals, Forest Low Enforcement, Governance and Trade (FLEGT) and many other reporting requirements, for example, ITTO and other regional C&I initiatives. Moreover, most of the regimes and policies have their own reporting requirements with specific reporting formats and time periods. This demands a harmonized forest-related reporting at the national level (Neupane 2018, Köhl et al. 2020). Therefore, countries require a more integrated process of collecting, handling, disseminating, and sharing information to meet the data needs of the multiple reporting requirements. Most of the high-performance and rewarding indicators and associated variables selected by the participants in this study are able to serve the data needs for multiple reporting requirements. More importantly, most of the data/information related to the population-species level are being/can be collected by routine forest inventories (e.g., national forest inventories under FRA, pre- and post-inventories by forest concessions, forest inventories by communities under CBFM). Integrated data collection, handling, processing, analysis, interpreting, and sharing might reduce the costs of NFMS/NFIS substantially (Neupane et al. 2019, Köhl et al. 2020).

The countries seeking to obtain the result-based payments under the REDD+ mechanism should provide information on how the Cancun safeguards are addressed and respected throughout the implementation of the REDD+ activities (Decision 1/CP.16 paragraph 71 (d)). Safeguards can be most effectively addressed, if the biodiversity aspects are considered during the planning and design, implementation, and
FIGURE 4 Quantity of highly rewarding/high performance indicators (percent of collectively selected indicators) applicable to forest management unit level forest biodiversity monitoring system selected by different combinations of expert panels. F = Expert panel constituting the representatives from forest management units (FMUs), forestry concessions and other field level forestry professionals; A = Expert panel constituting the representatives from academics (i.e., Universities) and research institutes; and G = Expert panel constituting the representative from government agencies (mostly decision making level)

assessments of the REDD+ process. With increasing emphasis on social and environmental safeguards for REDD+, and work on biodiversity conservation (CBD), there is a growing concern for biodiversity monitoring for REDD+. The selected high-performance and rewarding indicators are not only useful for biodiversity monitoring, but equally useful to integrate biodiversity monitoring in general to the carbon MRV system under the NFMS of REDD+.

There is an increasing awareness that the long-term protection of biodiversity requires inclusion of flexible restoration along with protection (Perino et al. 2019). The UN General Assembly recently designated 2021–2030 as the “decade of ecosystem restoration”. In this study, participants have selected several landscape level indicators as rewarding indicators. ‘Forest and forest land restoration’ and ‘forest condition’ related attributes constitute structural indicators at ecosystem-habitat level. The selection of such indicators by the expert panels reflects their contemporary viewpoints to the recent development of international policies related to avoiding deforestation, forest landscape restoration, and biodiversity conservation.

Application of the highly rewarding indicators in establishing a PFBMS at local/FMU level

After the application of the three filters (initial filters: availability of expertise and services, primary filters: indicator responsiveness and cost efficiency, secondary filters: relevancy and generality to application) highly rewarding indicators were selected in the study. Interestingly, the indicators list selected after applying all three filters resulted in almost completely different sets of indicators among the three group of experts, with only 4 common indicators. In addition, 12 indicators were common to at least two expert group. This reflects the importance of engagement of diverse stakeholders and incorporating their views, concerns, and knowledge in biodiversity monitoring. This has been highlighted in several global/regional platforms and events (e.g., IPBES-7, International Indigenous Forum on Biodiversity and Ecosystem Services). However, most of the biodiversity indicator lists to date have been developed by international groups, scientists, and academicians. Local decision makers and stakeholders are often ignored in the process of developing and selecting indicators for the biodiversity monitoring system and many other processes lack this crucial aspect (Danielsen et al. 2000, Spellerberg 2005). These gaps are not persistent in biodiversity sector alone, but are also prominent in other processes related to the development, social, and environment sectors. This study integrated top-down into bottom-up as a mixed complementarity approach. In such an approach, the contribution of professionals ensures scientific rigor in program design and data analysis, and the involvement of local actors facilitates the process of implementing management recommendations, while also providing a reliable, cost-effective and sustainable means of data collection and a potentially rich source of local knowledge to aid interpretation of results. Consideration of the practical factors that determine the viability of designed monitoring program assures the success of the program.

Though the overall sustainability of a nation’s forests depends substantially on actions taken at the national scale, in principle, the national-level analysis of indicators may involve the aggregation of data collected at the local or FMU scale. Therefore, analysis of indicators at the FMU scale is the key to assessing, monitoring, and reporting on SFM (ITTO 2016). Since forests managed by the states, FMUs, FUGs and IPLCs outside the protected areas host most of the biodiversity, a monitoring tool that allows the FMUs and local stakeholders to track the progress towards the goal of sustainability is essential. Management of the forests is crucial not only for the persistence of many flora and fauna species and the conservation of the habitats they reside, but also for the people who depend on the forests for their livelihoods. At the same time, they enhance landscape connectivity (Gardner 2010). To achieve national biodiversity targets in line with the Aichi Biodiversity Targets 2011–2020 and post-2020 biodiversity targets, a country must maintain and promote its biodiversity in those forests. The process of selecting high-performance and rewarding indicators through a participatory approach and using such indicators to develop a monitoring system are significant to the development of an effective PFBMS.
Defining rewarding indicators at the local level by locals to assess changes in biodiversity and resulting impacts on other stand attributes

Assessing local changes in forest structure due to management practices and consequently its impact on species richness provides insights that are ecologically important and conservation relevant. But such studies are often hampered by a shortage of baseline data and the absence of long-term monitoring (Primack et al. 2018). Meanwhile, some researchers have highlighted a debate over how biodiversity is changing across the planet and at the local level, and biodiversity gains in local- vs global-scale species richness (e.g., Vellend et al. 2013, Cardinale et al. 2018, Primack et al. 2018). Vellend et al. (2013) suggested that over the last century there is no trend towards a decline in plant species diversity at the local-scale. A growing volume of literature has suggested a positive biodiversity effect on forest productivity and ecosystem functioning (Hooper et al. 2005, Vilà et al. 2007, Gamfeldt et al. 2013, Ruiz-Benito et al. 2014, Liang et al. 2016, Weisser et al. 2017, Hutchison et al. 2018, Zeller et al. 2018, Amara et al. 2019). In Catalonia, Vilà et al. (2007) found a significant positive association between local tree species richness and wood production and suggested that mixed forests had 30% more wood production than monospecific stands. More species are needed to insure a stable supply of ecosystems goods and services (Hooper et al. 2005). Liang et al. (2016) revealed that continued biodiversity loss would result in an accelerating decline in forest productivity. Hutchison et al. (2018) investigated diversity-stand stability relationship and suggested that diverse forests could be more resilient to stresses induced by global climate change. In Spanish forests, Ruiz-Benito et al. (2014) found diversity increases carbon storage and tree productivity. In Mexico, Martínez-Sánchez (2015) found that humid and sub-humid tropical forests with higher structural diversity tend to hold larger carbon stocks in their vegetation. Likewise, Ercanli (2018) observed a positive relationship between stand structural diversity and carbon storage for even-aged Scot pine stands in Turkey. Some studies presented contrasting results on the effect of structural diversity on stand productivity. Zeller et al. (2018) cautioned that structural heterogeneity can have positive or negative effects on stand productivity. Higher structure-species diversity results in multilayered canopy which might make stands more susceptible to devastating crown fires.

A PFBMS established by engaging all affected stakeholders at all levels and across society early on, i.e., when defining rewarding indicators and throughout the monitoring process, is of great importance for real-time monitoring in order to observe and verify such changes at the local level. Such a PFBMS derives lessons for improving management practices that promotes biodiversity conservation while maximizing the value of forest products and the services that forests provide, and thus contributes significantly to responsible forest management. The PFBMS generates such baseline data and paves the roadmap for the long-term monitoring.

Linking the changes in biodiversity with the management impacts

In Indonesia, a forest management unit can be defined as a specified operational forest area with a permanently demarcated forest boundary with a set of explicit economic, social, and ecological objectives expressed in a self-contained multi-year and long-term forest management plan. FMUs are responsible for ensuring that SFM is implemented. In Indonesia, FMUs are managed by a legally established localized body called ‘Kesatuan Pengelolaan Hutan or KPH’ and they are categorized based on the dominant forest types/forest functions as a: Conservation FMU, Protection FMU and Production FMU. For forest biodiversity monitoring to be meaningful, a clear understanding of the goal and objective (what and why?) of the monitoring is necessary. For instance, in a managed forest (i.e., a Production FMU), the purpose for monitoring could be to minimize the impact of management interventions on the forest biodiversity and the ecological processes. The monitoring of protected areas or conservation areas could be done to assess particular sets of species, or particular elements of biodiversity or ecological integrity as a whole. Ecological integrity is defined as the capacity of ecosystem to support and maintain a community of organization that has structural, compositional, and functional organization comparable to that of a similar yet undisturbed ecosystem. Once the purpose for the monitoring is clear, the next step would be the formulation of specific questions to be answered by monitoring. These questions are formulated based on the identified goals and objectives. For instance, we might want to explore whether forest management practices comply to agreed standards and goals of the SFM. If it is so, they might still have an impact on biodiversity. The indicators selected should link the changes in biodiversity with the management impacts. The framework used in this study defines and determines the high-performance and rewarding indicators which are, among other features, sensitive to management impact/disturbance and relevant to biodiversity conservation goals.

Open, transparent, logical, and stepwise approach to selecting indicators

The development/selection of indicators for biodiversity monitoring should be a flexible concept. This demands continuous effort to ensure that the selected indicators are responsive to the new global challenges, forest related international processes and their reporting requirements, and to emerging developments in economy, societal, and environmental realms. The indicators’ responsiveness to emerging developments to the local economy, societal, and environmental realms (jurisdictions such as Province, state); to opportunities for coordination and collaboration with other international processes and national forest/environmental related reporting processes, for example, REDD+ MRV, to forest inventories in harmonizing the underlying definitions
and data collection, storage and reporting are other considerations in selecting the indicators. Conservation needs the wider society and stakeholders to stay engaged and continue to work toward solutions (Costello 2019). This study provides an open, transparent, logical, and stepwise approach to selecting the indicators for FMU level PFBMS. Such an approach gives stakeholders the confidence that their values are being maintained (Hagan and Whitman 2006) and this ultimately enhances the legitimacy of the outputs. The same approach can be applied to the selection of indicators at different levels and across sectors.

CONCLUSIONS

The integrated approach to developing indicators in this study combines the expert guidance and management experience provided by professional scientists with the important practical stakeholder involvement at the province and local (implementation) levels. It is very likely that the involvement of professional scientists in the process of adapting the multidimensional metaconcept for biodiversity ensured the scientific rigor of the selected 40 high-performance and rewarding indicators, while the involvement of local forestry and environment professionals helped to identify and select technically and logistically viable, effective and responsive, cost efficient, goal oriented and widely applicable indicators. Framing the globally available biodiversity indicators to the local context ensures a global-local connection; and engaging diverse stakeholders at all levels and across society, this approach maintains the essence of the participatory approach which is highlighted in CBD, IIFBES, IPBES-7 and UNFCCC Cancun Safeguards. Long-term monitoring data, scientific studies, and the strengthening of local capacity are critical for determining the intended outcomes and desired impacts of forest biodiversity monitoring. In the context of the rising need for a more integrated process of gathering, analyzing, sharing, and disseminating forest-related information between government agencies and programs to meet the consistent and comprehensive data demands of multi-national reporting requirements (e.g., FAO FRA, Aichi Biodiversity Targets and post-2020 biodiversity framework- CBD, Global Forest Goals- UNFF, UN SDGs, REDD+, NDCs and biennial transparency reports- Paris Agreement, National Communications- UNFCCC) at reduced costs and efforts, the selection of indicators using a hierarchical approach of diversity is highly desirable. One of the major hindrances to practice sustainable forest management is the lack of sufficient investments. In this study, FMU expert panel indicated that one-third of the high-performance and rewarding indicators cannot be monitored at present due to constrained financial/technical capacities. Similar constraints can be observed in most of the community-based forest management regimes. Strengthening the use of incentives available, for example, REDD+ incentives to overcome such financial/technical inadequacies at the FMU or CBFM levels will reinforce the outcomes of the sustainable/responsible forest management including biodiversity conservation as well as of REDD+. Moreover, choosing the aspects of biodiversity to monitor is one of the challenges in monitoring biodiversity for REDD+ (Dickson and Kapos 2012) and in monitoring biodiversity for forest management. The hierarchical approach defines biodiversity as a multidimensional metaconcept and enabled this study to define robust biodiversity indicators including all three ecosystem functions attributed to the four organizational levels.

The process of bottom-up and long-term multi-stakeholder collaborations as envisaged in this research must become the norm to realize the factual essence of a participatory forest biodiversity monitoring efforts on the ground. This enhances the cultural adaptation of the outputs and outcomes of the forest biodiversity monitoring and has the potential to harness a rich source of local knowledge to design an effective PFBMS. In this study, diverse stakeholders used an open, transparent, logical, and stepwise approach to select biodiversity indicators. Such an approach provides stakeholders with confidence that their voices and choices are recognized and respected and ensures local legitimacy of the outputs and outcomes. A locally legitimate PFBMS might serve as a valuable tool providing real-time monitoring data that could enhance the effectiveness of NFMS substantially.

Results from this study bring a new perspective on the development and implementation of forest biodiversity monitoring systems and biodiversity assessments at local levels. The frameworks are equally applicable in developing forest biodiversity monitoring systems at different levels, ranging from forest management unit level (FMU, Forest Concessions, Community Based Forest management) to provincial/state to national level, and aiming at the responsible management of all types of forests under diverse ownership and management.

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