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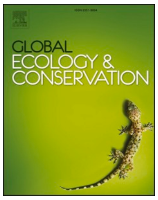

Progress on incorporating biodiversity monitoring in REDD+ through national forest inventories

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ABSTRACT

There is a well-documented opportunity and need to incorporate biodiversity conservation priorities into REDD+ (Reducing Emissions from Deforestation and Forest Degradation) initiatives. This requires thorough monitoring of changes to biodiversity at appropriate temporal and spatial scales. A national forest inventory is one of the essential tools used to monitor carbon stock changes but can also be expanded to include biodiversity indicators. Here we analyse the progress and potential of 70 countries in monitoring primarily non-tree biodiversity using national forest inventories. Progress on national forest inventories among countries participating in REDD+ is variable: 11 countries have not started; 26 have started but do not include non-tree biodiversity indicators; the remaining 33 countries do include non-tree biodiversity indicators but use various methodological approaches, levels of detail and taxonomic groups. Very few of these provide comprehensive and accessible manuals or results, highlighting a need for greater transparency. The capacity of countries to fund ongoing national forest inventories is a constraining factor. Remote sensing technologies can help reduce costs for countries with limited monitoring capacity but the need to understand biodiversity variation at finer scales often limits the utility of such methods.

1. Introduction

REDD+ (Reducing Emissions from Deforestation and Forest Degradation, plus the sustainable management of forests, and the conservation and enhancement of forest carbon stocks) holds great potential to reverse the current trend of deforestation and forest degradation (FAO, 2016), which together account for around 12% of global anthropogenic emissions (van der Werf et al., 2009).

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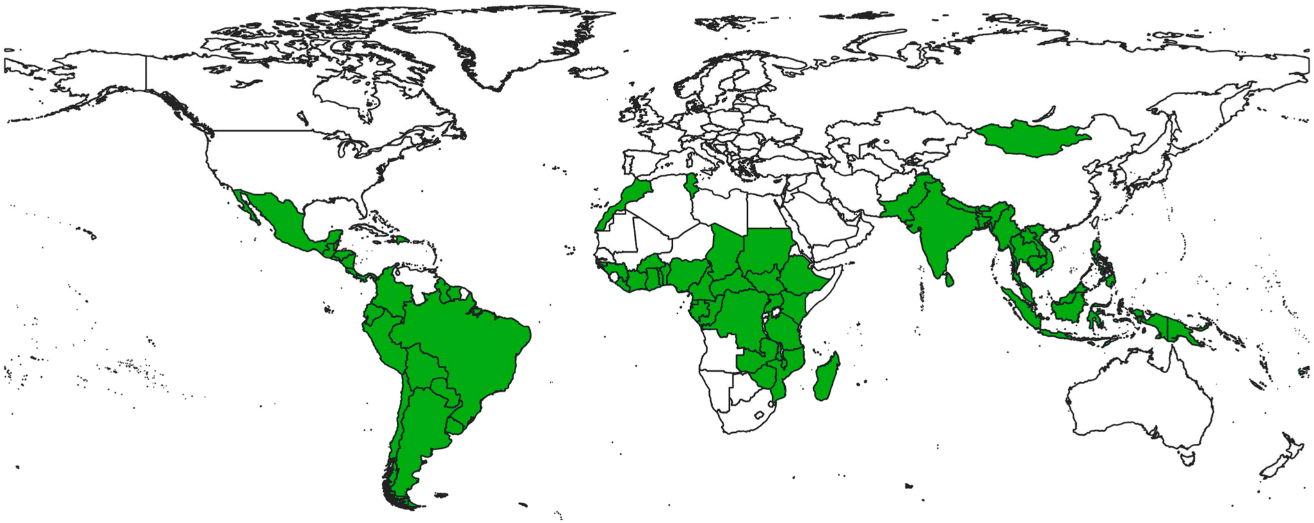

Fig. 1. Map showing the 70 countries included in this review highlighted in green.

Forests host the largest share of the world's terrestrial biodiversity (Parrotta et al., 2012), so REDD+ can simultaneously represent a much-needed buffer against the ongoing, though comparatively underestimated, biodiversity crisis (Gardner et al., 2020; IPBES, 2019). Long-term carbon storage and biodiversity are at the same time mutually dependent (Hinsley et al., 2015; Parrotta et al., 2012), as the potential of forests for climate regulation depends on their intactness (Gardner et al., 2019; Lewis et al., 2019). However, REDD+ actually embodies potential risks for biodiversity (Huettner, 2012; Phelps et al., 2012), such as the incentive it could present to convert natural forests to monocultures of highly productive tree species (Dickson and Kapos, 2012; Parrotta et al., 2012; Pistorius et al., 2011) or by increasing land-use pressure on carbon-poor but highly biodiverse areas (Bayrak and Marafa, 2016). Moreover, protecting forest cover and carbon stock alone will not automatically insure species diversity (Beaudrot et al., 2016; Collins et al., 2011; Ferreira et al., 2018; Pandey et al., 2014; Paoli et al., 2010), as other anthropogenic threats such as wild resource overexploitation, biological invasions and especially hunting can still affect the forest's biodiversity and, indirectly, even carbon stocks themselves (Hinsley et al., 2015; Krause and Nielsen, 2019).

To deflect potential collateral damage caused by REDD+, a series of social and biodiversity safeguards were introduced. These are however neither directly enforced, nor is it specified how they should be addressed and respected for countries to ultimately access result-based payments (UNFCCC, 2014). Instead, it is up to countries to interpret safeguards in the context of existing national frameworks (UNFCCC, 2012) and this flexibility offers opportunities to reinforce conservation efforts within national REDD+ strategies (Pistorius et al., 2011). In any case, countries need to be able to track trends in biodiversity and make them attributable to REDD+ in a robust and transparent way (Dickson and Kapos, 2012; Tyrrell and Alcorn, 2011), which can be achieved with a national forest inventory (NFI).

NFIs are technical means used to inform the overarching national forest monitoring system (NFMS) required by the Warsaw Framework (FAO, 2018a; UNFCCC, 2014). Although the implementation of NFIs has been supported since the 1960s in developing countries, they were unfortunately often limited to single unrepeated measurements (FAO, 2017). Their revision and replication are now further incentivized through financial support linked to REDD+ (Gizachew and Duguma, 2016), because the NFI represents one of the three key pillars of a robust and transparent Measuring, Reporting and Verification (MRV) scheme under the NFMS (FAO, 2018a). Widening the NFI's scope by including biodiversity indicators can provide credible information to transparently report on outcomes from efforts to address biodiversity safeguards (Epple et al., 2011; Gardner et al., 2012) and is already common practice in high-income countries (Chirici et al., 2012; Tomppo et al., 2010). Such indicators can for example include tree, shrub, plant and bird species in general, reflect the volume in living and dead biomass, or describe the forest vertical and horizontal structure (Chirici et al., 2012). When resources are limited such as under REDD+, the priority can be given to a selected set of taxa of special interest which are affordably sampled (Kessler et al., 2011) such as pollinators, large seed dispersers, alien invasive species, endangered species and forest-dependent organisms (Hinsley et al., 2015; Newton and Kapos, 2002; Tyrrell and Alcorn, 2011). An additional benefit of such a multipurpose NFI is that it can be used to comply with National Biodiversity Strategy and Action Plans existing under the Convention on Biological Diversity (CBD), whose targets are well-aligned with REDD+ and therefore represents important potential synergies (Dickson and Kapos, 2012; Epple et al., 2011; Gardner et al., 2012; Latham et al., 2014; Tyrrell and Alcorn, 2011) while increasing monitoring cost-efficiency through co-funding (FAO, 2017; Maniatis et al., 2019).

There have been considerable positive developments regarding NFMS but much progress is still needed (FAO, 2018b). Although some recent reports highlight the current global progress in monitoring capacities and NFIs in general (FAO, 2018b; Neeff and Piazza, 2019; Romijn et al., 2015), to our knowledge, none portray the biodiversity monitoring potential of NFIs. This comprehensive and detailed review of the state of the art of NFI's of the 70 countries participating in REDD+ aims to: (i) summarize progress on the implementation of biodiversity indicators in NFIs, (ii) highlight observed methodological strengths and weaknesses, and (iii) propose recommendations for effectively tracking biodiversity changes during REDD+ implementation based on best practices and scientific evidence.

2. Materials & methods

We conducted an extensive literature search on NFIs in the context of REDD+ in December 2019 and January 2020. This review hence reflects the situation up until that point in time. The countries were limited to the participants of the two most prominent REDD+ programmes: the United Nations REDD+ programme (UN-REDD) and the World Bank's Forest Carbon Partnership Facility (FCPF). Brazil, operating under the Amazon Fund (http://www.amazonfund.gov.br/), was also added to the list, totalling 70 countries (see Fig. 1). Documents in all national languages were considered. Our REDD+ document review followed three consecutive steps described below.

First, we compiled a collection of country-specific documents. Searches were in a first instance focused on the three major web platforms used by countries to share progress on REDD+ : the UNFCCC REDD+ Web Platform (red.unfccc.int), the UN-REDD Programme Collaborative Workspace (unredd.net) and the FCPF country submissions (forestcarbonpartnership.org). Together, these web platforms generally contained most important and representative national documents, but still often failed to provide sufficiently detailed information on NFIs. Those documents were nonetheless most often valuable for assessing NFI progress or to rule out the existence of concrete NFI documentation. The same holds for country-specific updates on the FAO website (fao.org) or national newspapers. Detailed documentation or results were also sometimes found on national REDD+ websites, national forestry department websites or repositories such as the very useful documentation centre for some participants of Central America and Caribbean states (reddccadgiz.org). Vanuatu is the only country that provided a clear manual in its Readiness Preparation Plan, a mandatory document for FCPF participants. Another example is the case of Mongolia, for which methodological details were found in a peer-reviewed scientific paper (Altrell, 2019). In total, information was retrieved from 319 reports and websites for an average of about 4.5

documents per country. See Appendix for the complete list of sources.

Second, we searched for terms related to NFIs in each document. The term 'national forest inventories' was most frequently used, although there were many equivalent exceptions such as the Bangladesh Forest Inventory (BFI), Zambia's Integrated Land Use Assessment (ILUA) or Tanzania's National Forestry Resources Monitoring and Assessment (NAFORMA). When the existence of an NFI was confirmed, we verified whether it was actually linked to REDD+ . We then typically proceeded to searching for field manuals and NFI results, which are the most reliable sources of information.

Third, we searched for biodiversity-related information, in the broad sense. Biodiversity is defined as the variety of life on earth at the genetic, organismal and ecological scale (Heywood and Watson, 1995). Here, however, countries essentially considered species diversity and indicator species (except for Panama that also samples functional diversity of herbaceous plants). When a manual was obtained, we searched for any reference to the monitoring of biodiversity indicators and mentions of including non-tree flora, fauna and other organisms. Mentions of special types of tree groups such as palm and fern trees were therefore not included. The species of a sampled tree is typically recorded during an NFI, which is why this review lays emphasis on non-tree biodiversity. Even though tree biodiversity monitoring could therefore be monitored through these data, this is not necessarily the case. This is why explicit mentions of tree diversity monitoring such as for Bhutan, Colombia and India were given extra attention and reported (see Appendix).

On some occasions, manuals or results were not accessible even though other documents confirmed their existence. Some websites referred to in documents were not accessible or outdated (e.g. for Laos, Mozambique and Sri Lanka), or insufficient details were given about the possibility to obtain this information. Note that we only present the *potential* of countries to monitor biodiversity, not what is or will be applied in reality. This is, on the one hand, because some countries clearly developed their methodologies but are either yet to initiate the field measures or are currently conducting the inventory work. On the other hand, it was often very challenging to access results and especially clear information on how biodiversity indicators will be actually used in practice.

All resulting information was compiled and is made available in the Appendix. This includes a summary on NFI progress and on the biodiversity indicators chosen by each country, together with the full list of relevant national documents and weblinks, sorted by country and document type. This repository can be used as inspiration to improve the inclusion of biodiversity indicators within the NFI, and as a basis to keep track of further developments.

3. Results & discussion

3.1. General progress on national forest inventories

There is substantial variation in overall REDD+ progress between participating countries (UNREDD, 2018). This is reflected in the diverging capacities for MRV (FAO, 2018b; Neeff and Piazza, 2019; Romijn et al., 2015), which NFIs are an essential part of (Maniatis and Mollicone, 2010). A large gap between continents is evident, with Latin America having the most accessible, comprehensive and detailed methodologies and Africa representing the area with most potential for development (Fig. 2). On the one hand, some countries have a long history of forest inventories and may already have conducted multiple cycles (e.g. India, Mexico and Vietnam). This gives those countries an important 'head start', even though inventory methodologies must be adapted for REDD+ reporting. On the other hand, some countries experience very slow and challenging implementation phases due to either a lack of experience (e.g. Benin, Central African Republic and Jamaica) or due to safety issues that limit physical accessibility to sampling plots such as in Myanmar. A previous review of national inventory capacities of 99 countries corroborates the observed differences among continents but also highlights the potential for knowledge transfer to close existing gaps (Gizachew and Duguma, 2016; Romijn et al., 2015).

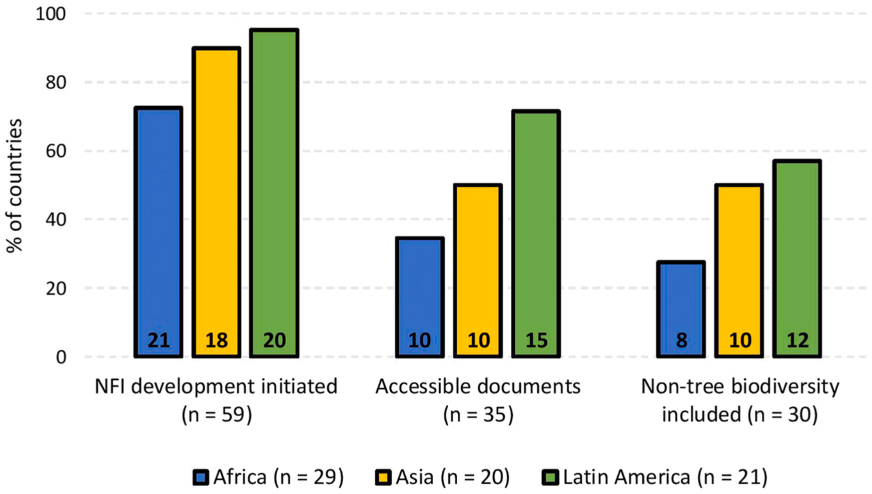

Fig. 2. Proportion of countries of each continent as a function of progress on national forest inventories. At the bottom of each bar the absolute number of countries per continent is reported. A total of 70 countries were assessed in December 2019 and January 2020.

Out of 70 countries, 59 have at least initiated developing an NFI (84%) (Fig. 2). This proportion matches the progress recently reported by the Food and Agriculture Organisation (FAO) based on the countries having submitted a Forest Reference Level for REDD+ (also 84%) (FAO, 2019). From 59 countries that initiated their NFI's development, 35 reported the completion of the NFI or had planned completion by March 2020. In seven cases, it was unclear whether NFIs had been completed. Regardless of NFI completion, 35 out of 59 countries had accessible information on methodological details, be they field manuals or results (Fig. 2).

The FAO supports countries in developing an NFMS by providing guidelines (FAO, 2018a) and conceived a template NFI manual (FAO, 2012). However, our review revealed that only eight countries adopted designs that resemble FAO's template, likely because the template was meant for specific situations where financial resources are limited and the area's topography allows sampling long transects. Instead of a standardized method, we found a plethora of different sampling designs, together accounting for over 15 markedly distinct designs. Sampling units were constituted of either rectangles, squares, crosses or circles, each of which are sometimes replicated to form clusters and often contain different degrees of subplot nesting (Table 1 and Appendix).

3.2. Biodiversity indicators and national forest inventories

In the context of an NFI, biodiversity indicators typically include the assessment of forest flora and fauna in specifically allocated subplots (FAO, 2012). For REDD+, countries are nevertheless flexible in elaborating their MRV schemes (UNFCCC, 2012) and can thus decide which taxonomic groups to consider, or even choose not to include any indicators at all. Regardless of whether detailed methodological documents were available, 33 out of 59 countries that initiated NFI development mentioned the inclusion of non-tree taxa (Fig. 3). Three of these share no more detail than 'fauna' or 'flora'. Eight countries defined more precise indicators but did not provide sufficient details for understanding the methodology. For example, some countries mentioned specific groups such as bamboos, lianas and herbs, but field manuals or results were not found to confirm whether these were actually included and how they would conduct the sampling. Twenty-two countries provided a minimum level of methodological details. Yet, it is important to note that large differences in detail and scope still exist within those countries. Some countries merely assessed the coverage of plant functional groups per subplot, others proceeded with an extensive botanical survey to identify species to species level and used advanced techniques for faunal observations.

Out of the thirty countries for which at least some detail on considered taxa was available (Fig. 3), 14 included only flora, three included only fauna and 13 included both flora and fauna. Most commonly considered non-tree woody flora includes shrubs, bamboo and lianas (vines). Herbaceous taxa included a variety of different groups such as grasses, ferns, mosses, succulents, epiphytes or most often simply 'herbs'.

For faunal diversity, there is also substantial variation among countries. The majority of countries focuses on large mammals and some countries specifically mention primates (i.e. Congo, the Democratic Republic of the Congo and Gabon). The Democratic Republic of the Congo provides a list of 15 large mammals guiding observations and Bhutan used collected data to model distribution maps for nine large mammals. In many countries, animals are not only observed directly but also by identifying footprints, sounds, nests, skin, feathers, faeces, corpses and bones. Honduras and Mexico even use camera traps, a cost-efficient means to capture the presence of larger animals (Waldon et al., 2011). A minority of countries include invertebrates in their assessments, again with a lot of variation in the scope of sampling. For example, Madagascar plans to include pollinators, mentioning bees and butterflies but without giving further specifications. Chile and Nepal elaborate more on applied sampling techniques, but Papua New Guinea presents the most detailed information, with comprehensive descriptions on the sampling of moths, ants and fruit flies. Lastly, five countries consider either mushrooms (from a preselected list) or lichens (coverage), though it is very unclear for two of these countries whether this is or will be actually applied.

In some cases, such as for Nepal, Vanuatu and Zambia, non-tree taxa are included under the category of non-timber forest products (NTFPs). Details are often lacking (e.g. no species identification) or the range of NTFPs is quite restricted such as in the Democratic Republic of the Congo, which stipulates a list of 10 herbaceous species. Argentina uses a similar approach, but based on a more extensive list of 68 key species including shrubs, herbs, vines, ferns, epiphytes, succulents and mushrooms.

Even when some forms of non-tree diversity are included, the countries explicitly stating the incentive to monitor biodiversity in function of REDD+ implementation and/or biodiversity safeguards is very restricted. Notable examples include Chile, Fiji, Gabon, Nepal, Papua New Guinea and Vanuatu, some of which also expressed intentions to combine efforts to comply with commitments made under the CBD (e.g. Nepal and Vanuatu). Even if not stated explicitly, many countries are nonetheless undertaking significant efforts to include biodiversity measures. Table 1 illustrates some of the better practices and the variation in methodologies adopted among countries. The main goal here is to highlight the diversity of possible approaches, which can serve as inspiration for countries that have yet to develop their NFI or want to upgrade their methodologies to incorporate biodiversity. A full table summarizing approaches from the 70 countries is made available online for researchers and policy makers to update and to keep track of advances (see Appendix).

3.3. Advantages of monitoring biodiversity using national forest inventories

The main rationale for including biodiversity indicators into NFIs is one of efficiency. That is, it allows to simultaneously detect changes in carbon stocks and biodiversity over time at the national scale (Epple et al., 2011) and consequently circumvent the costs of developing a separate biodiversity inventory (Corona et al., 2011) or having to merge scattered and incomparable subnational data (Entenmann et al., 2014). Observed biodiversity changes can be reliably correlated with carbon stock changes because assessments were made at the same time and place (Corona et al., 2011; Gardner et al., 2012; Motz, Sterba, and Pommerening, 2010), increasing the transparency and scientific soundness of the MRV. The field-based sampling of permanent plots and the potential for detecting

Table 1
Detailed overview of the progress and methodologies on national forest inventories (NFI) for a selection of ten countries. Countries were selected to highlight good examples of different continents and the variety in adopted methodologies. Although subplot sizes for biodiversity differ drastically, these need to be considered in function of the number of plots and level of biodiversity assessment detail. Also note that some countries opted to sample their whole territory while others, such as Mongolia, did not because of a low forest cover. See Appendix for the whole summary of 70 countries’ progress and methodologies together with references to compiled documents. BD = biodiversity, NTFP = non-timber forest products, SOI = summary of Information, FRA = forest resource assessment, FCPF = Forest Carbon Partnership Facility.

Country	UN-REDD	FCPF	Progress	Sampling unit design	Plot size (m^2 x number)	BD subplot size for flora (m^2 x number)	Number of plots	Country size (km^2)	Sampling density (plots/ 1000 km^2)	Included taxa	Comment
Gabon	✔	✔	Will be established by 2023 but pilot completed in 2018 (104 plots)	Cluster of one large and four small square plots with rasters of subplots	1000 + 4 × 160	NA	500	267.667	1,87	Trees, lianas and mammals.	The NFI is explicitly linked to the monitoring of BD co-benefits for safeguard ’e’. It includes a full botanical survey, with focus on highly diverse areas and a habitat qualification. Wildlife surveys focus on mammals, specifically great apes and elephant populations, assessed through direct observation or by searching for ape nests and elephant dung.
Mexico	✔	✔	Three cycles done using updated methodology	Cluster of four circular plots with two levels of nested subplots	400 × 4	1 × 4	26220	1.972.550	13,29	Trees, shrubs, lianas, canes, bamboo, succulents, herbs, grasses, ferns, epiphytes, mosses, lichens and fauna.	Plants are described according to an extensive list of growth forms (e.g. Rosette, solitary herb,.) and identified till species level. Mosses and lichens assessed according to coverage. Invasive species are given species attention. Camera traps set up for recording fauna, targeting most likely large mammals.
Mongolia	✔		Boreal zone and saxaul forests completed	Cluster of three circular plots with three levels of nested subplots	1257 × 3	113 × 6	4367	1.566.000	2,79 (grid of 1,5 ×1,5 to 9 ×9 km, only in forested areas)	Trees, shrubs, sub-shrubs, lianas, herbs, grasses, ferns, mosses and lichen.	Only red-listed species are identified. Within a subplot, the number of different plant species is counted and the coverage of the different vegetation groups is estimated.
Nepal	✔	✔	NFI completed in 2014 and 96 PSPs added in 2018	Single circle with five levels of nested subplots	1257 × 1	1 × 4	1600	147.181	10,87	Trees, shrubs, herbs, grasses, rare or endangered trees, large and small mammals, birds, herpetofauna, butterflies, moths and other insects.	FRA plots sampled in 2010–2014 are used both for the NFI and BD monitoring. Tracking of REDD+ impact on BD is explicitly mentioned. Besides the listed taxa, a list of 46 NTFPs is provided. Detailed methods for sampling of the different taxa are available.
Papua New Guinea	✔	✔	First cycle done in 2016–2019	Cluster of four circular plots, of which central plot for BD	314 × 4	314 × 1	1000 planned, 46 sampled	462.840	0,10	Trees, shrubs, lianas, giant herbs, herbs, ferns, mammals, birds, herpetofauna, moths, ants and fruit flies.	BD explicitly included to monitor REDD+ impact. Information used to compute diversity indicators at taxon level, but also at structural and functional level (measuring of plant functional traits). Very detailed manuals with group-specific methodologies easily accessible.

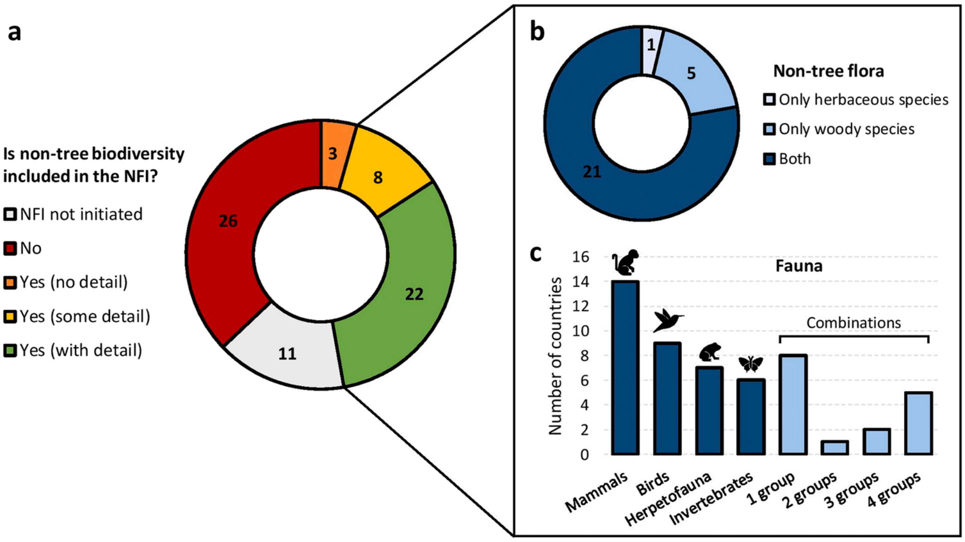

Fig. 3. (a) Number of countries mentioning the inclusion of non-tree taxa in their national forest inventory. For countries providing a minimum of specifications on included taxa (i.e. more than only 'fauna' or 'flora'), the main broad groups of considered flora (b) and fauna (c) are illustrated. 13 out of these 30 countries sampled both flora and fauna. Numbers denote how many countries correspond to each category. Note that this overview conceals the many country-specific methodologies and diverging levels of detail. Refer to Table 1 and Appendix for more specific information.

species-level changes provide the most credible reporting, which can be used to comply with commitments under REDD+ and CBD at the same time concerning forest ecosystems (Chirici et al., 2012; Gardner et al., 2012; Tyrrell and Alcorn, 2011). Furthermore, reporting may benefit from creating and reinforcing linkages between the NFI and other existing inventories such as the Forest Resource Assessments conducted every five years by FAO (Maniatis et al., 2019). The national scale ensures the inclusion of low-carbon but unprotected, highly biodiverse areas that may not be prioritized for conservation efforts under REDD+ and therefore experience increased land-use pressure (Bayrak and Marafa, 2016; Huettner, 2012; Phelps et al., 2012). For example, such 'leakage' was observed and discussed in Indonesia, where most REDD+ projects focus on carbon-rich peat swamp forests (Harrison and Paoli, 2012). This risk can be tracked through systematically dispersed permanent plots covering the whole territory. This is sometimes not the case, as countries with very low forest cover proportion such as Mongolia rather apply subnational inventories.

To a certain extent, biodiversity monitoring can be complemented or even enhanced by using remote sensing (O'Connor et al., 2015), including drones (Zhang et al., 2016). Initially, by identifying overlapping areas most susceptible to changes in carbon and biodiversity, but also by quantifying tree and canopy structural characteristics as proxies for tree species composition, habitat diversity and animal species richness (Goetz et al., 2015; Vihervaara et al., 2017). High-resolution remote sensing then allows to monitor changes in carbon stocks and biodiversity through time over the whole national territory, including inaccessible areas, and at reduced costs (O'Connor et al., 2015; Vihervaara et al., 2017), something not feasible based on field observations alone (Nagendra, 2001). However, remote sensing goes hand-in-hand with field-based inventories which are needed for calibration and validation of biodiversity metrics (de Sassi et al., 2015; Goetz et al., 2015; Nagendra, 2001; Vihervaara et al., 2017), thus providing a baseline measure for remote sensing monitoring. The more information is collected to solidify that baseline, the more accurate and relevant the national-scale remote sensing becomes. Given that recurrent NFIs may be unrealistic due to likely depletion of REDD+ readiness funding, it is good practice for these carbon-financed NFIs to also include a robust biodiversity component. Repeated NFIs coupled with remote sensing, nevertheless, still represent the ideal solution, among others because remote sensing alone is limited in directly assessing several taxonomic groups (Kuenzer et al., 2014). Fortunately, integrating biodiversity into an NFI is not necessarily dramatically more expensive.

3.4. The cost of including biodiversity in national forest inventories

Conducting a national-scale inventory only for carbon stock estimation can already represent a challenge for countries where inventory capacities are historically low and implementation is lagging (Gizachew and Duguma, 2016; Neeff and Piazza, 2019; Ochieng et al., 2016). Including non-tree taxa may add complexity, financial costs and time, and may thus simply not be considered a priority (Dickson and Kapos, 2012). Additionally, biodiversity assessments require a lot of taxonomic expertise and knowledge, which may be especially limiting in tropical regions (Grussu et al., 2014; Lawton et al., 1998; Slik et al., 2015). Compromises must thus be found, but lessons learned from other countries already present promising solutions.

Nicaragua combines the monitoring of biodiversity with NFIs by allocating 10% of permanent plots for biodiversity assessments. Chile applies a similar approach, with a simplified assessment of all sampling units but a more detailed survey in areas of high biodiversity in the Mediterranean region. Bangladesh goes further by adapting the sampling density to each of five strata (Henry et al., 2021). Increasing sampling efforts where biodiversity is high and/or most likely to change as a result of REDD+ and human activities in general can be an option to increase sampling cost-efficiency (Gardner et al., 2012; Grussu et al., 2014). Another method adopted in Mongolia and the Philippines is to perform a simple counting of different species within a given area, without identifying them. When sufficiently replicated, this could represent a compromise for an easily obtained diversity metric, though a lot of other interesting information such as the presence of rare, invasive or keystone species and any measure of relative species abundances is ignored. A third approach is the predefined selection of 68 non-tree species by Argentina. Developing an area-specific list of keystone indicator species could provide relevant information on forest while avoiding the substantial time and expertise needed for systematically identifying all species within an area (Hinsley et al., 2015), though the list needs to be broad enough to be representative of the region-specific biodiversity (Lindenmayer et al., 2000).

In Papua New Guinea, the country that conducted one of the most ambitious and systematic assessments, the total cost related to including biodiversity such as birds, ants, moths, fruit flies and non-tree plant species was about USD 780.000 based on all necessary training, materials and salaries. This is about 12% of the total budget for the NFI (USD 6.754.887) (FAO, 2020). A review on project-level initiatives in Peru similarly reported small investments relative to total REDD+ implementation costs (Entenmann et al., 2014).

Engaging local communities in carbon stock accounting and monitoring can have social co-benefits (Danielsen et al., 2013; Larrazábal et al., 2012; Palmer Fry, 2011; Pratihast et al., 2013), but can also generate biodiversity information (Pratihast et al., 2013; Zhao et al., 2016). For example, a case study in China illustrated that local communities can conduct tree diversity inventories with similar accuracy as experts when well-trained, but at one third of the cost (Zhao et al., 2016). As is the case for integrating biodiversity, social co-benefits are also preeminent for REDD+ viability (Visseren-Hamakers et al., 2012).

3.5. *Biodiversity indicators of interest for REDD+*

The choice of indicator taxa needs to combine resource efficiency and ecological accuracy. Because the NFI automatically provides information that could be used to derive diversity indices based on tree species and abundances (Dickson and Kapos, 2012; Motz et al., 2010), there is great interest in using trees as a 'surrogate taxon' for overall forest biodiversity. Although this would allow affordable surveys (Imai et al., 2014) and tree community composition measures can be effectively coupled to remote sensing for monitoring at a larger scale (Fujiki et al., 2016), sampling only trees as a surrogate taxon is unfortunately insufficiently representative for forest biodiversity (Kessler et al., 2011; van Weerd and Udo de Haes, 2010).

Using a single taxon or group such as trees with consistently high cross-taxon congruency is frequently contested (Harrison et al., 2012; Howard et al., 1998; Kessler et al., 2011; Lawton et al., 1998; Lindenmayer et al., 2000) and depends on spatial scale (de Andrade et al., 2014; Westgate et al., 2014). Alternatively, the monitoring should rather specify a suite of different site-specific indicators matching agreed conservation goals for each occurring ecosystem type (Carignan and Villard, 2001; Harrison et al., 2012; Howard et al., 1998; Paoli et al., 2010; Westgate et al., 2014). Maximizing the amount of included taxa while prioritizing those which are cheapest to sample may be an appealing compromise (Kessler et al., 2011).

Not all taxa are equally suitable as indicators (Gardner et al., 2008; Kessler et al., 2011). Generally promising taxa include most notably birds, butterflies, dung beetles and wasps, especially because of their cost-effectiveness (Gardner et al., 2008; Kessler et al., 2011). Special attention should be given to forest-dependent species, alien invasive species and endangered or rare species (Newton and Kapos, 2002; Tyrrell and Alcorn, 2011). Indicator taxa of particular interest for REDD+ specifically are pollinators and large seed dispersers, as their disappearance may lead to a reduction in large tree recruitment and ultimately reduce carbon stocks (Hinsley et al., 2015). Large mammals and birds should be monitored because of their particular importance for ecosystem functioning (Jorge et al., 2013; Sekercioglu et al., 2004), their indirect but pivotal role for long-term carbon storage and the high hunting pressure directed towards them (Brodie and Gibbs, 2009; Hinsley et al., 2015; Krause and Nielsen, 2019). This role, and the fact that not all animals will benefit from maintaining sufficient tree cover alone, emphasizes once more that biodiversity should be inextricably linked to REDD+ (Collins et al., 2011). The monitoring of well-defined groups of organisms can be complemented with stand- and landscape-level forest characteristics such as forest maturity, stand complexity, extent, degradation, fragmentation and connectivity (Beaudrot et al., 2016; Lindenmayer et al., 2000; Newton and Kapos, 2002; Tyrrell and Alcorn, 2011).

4. Conclusions and recommendations

The NFI can reconcile the simultaneous monitoring of carbon stock and biodiversity changes needed to transparently demonstrate how biodiversity safeguards are respected. It also offers potential synergies with other biodiversity conservation and monitoring mechanisms such as under the CBD, increasing the cost-efficiency. At the moment, only few countries have grasped this opportunity. Out of 70 countries, about 30 have considered sampling non-tree taxa, but only few of those present detailed methodologies in line with recommendations for biodiversity monitoring. Furthermore, the necessary NFI repetitions through time may be jeopardized in many countries due to low capacities in terms of existing expertise or financial resources. Best practices and compromises currently implemented in the context of REDD+ are therefore highlighted in this review.

Improving cost-efficiency, a relevant list of keystone species that are indicative of forest health, based on country- or area-specific scientific evidence can be developed (Harrison et al., 2012). This can be complemented with metrics quantifying structural forest characteristics related to biodiversity and compatible with remote sensing. The NFI should include permanent plots distributed at the national scale to be able to detect any potential leakage effects, though the sampling density can be higher in those areas most likely subjected to changes in carbon storage and biodiversity. Monitoring can also be done by trained local community members, further reducing the cost.

When financially and logistically possible, the multipurpose NFI should be repeated through time for the most precise and accurate measures of biodiversity. For those countries lacking needed capacities and preferring to substitute such repetitions using more affordable remote sensing, we nevertheless recommend conducting an initial field-based inventory with various biodiversity indicators to provide a robust baseline. Field-based inventory efforts should still be applied at regular time intervals in the future to capture the biodiversity information that cannot be detected by remote sensing, but can be done on a subsample of permanent plots that are either randomized or located where largest changes in carbon and biodiversity is expected.

Additionally, we advocate for making NFI methodologies and results more transparent. Most countries describe their methodologies in their Forest Reference Emission Level (FRL/FREL) submissions or their national REDD+ webpages, with many exceptions. Adding to this inconsistent reporting is the fact that detailed NFI documents were often very hard to find, for example due to inaccessible links or pages. In some cases, manuals and results were most likely not publicly available. We therefore propose to consistently report on the methodological details as an annex to FREL submissions or by making manuals clearly available on national and international (e.g. reddccadgiz.org) REDD+ websites. A potential central repository for collected biodiversity data could also be the Food and Agriculture Microdata Catalogue, made by FAO to gather information from surveys, censuses and administrative sources (fao.org/food-agriculture-microdata). This option, however, also depends on countries' willingness to share data with FAO. To minimize the risk of endangered species poaching, some data such as plot coordinates might be anonymized. Transparency also implies providing more specificity regarding adopted methodologies. At the project level, biodiversity monitoring plans were found to be often too vague (Panfil and Harvey, 2016) and their outcomes are understudied (Duchelle et al., 2018). Our results show that this is echoed at the national level.

Action on both climate change and biodiversity loss is urgent. REDD+ needs to address both issues to guarantee long-term carbon storage and therefore its own viability. The programme is now well underway, with the first result-based payments approved and large amount of national experiences available (Maniatis et al., 2019). There is still time to reinforce the role of biodiversity as not only a co-benefit, but as an essential requisite for long-term success of REDD+.

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CRediT authorship contribution statement

Loïc Gillerot: Conceptualization, Investigation, Writing – original draft, Visualization. **Giorgio Grussu**: Conceptualization, Writing – review & editing, Supervision, Project administration. **Rocio C. Golec**: Writing – review & editing. **Rebecca Tavani**: Writing – review & editing. **Paul Dargush**: Writing – review & editing, Supervision. **Fabio Attorre**: Conceptualization, Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data statement

The table in Appendix provides a summarized overview of the 70 countries' progress regarding NFI development and implementation, as well as the inclusion of biodiversity indicators. The file also lists all used references per country and document type.

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Appendix A. Supporting information

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