An assessment of data sources, data quality and changes in national forest monitoring capacities in the Global Forest Resources Assessment 2005–2020

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Abstract

Globally, countries report forest information to the Food and Agriculture Organization (FAO) of the United Nations Global Forest Resources Assessments (FRA) at regular intervals. While the status and trends of national forest monitoring capacities have been previously assessed for the tropics, this has not been systematically done worldwide. In this paper, we assess the use and quality of forest monitoring data sources for national reporting to the FRA in 236 countries and territories. More specifically, we (a) analyze the use of remote sensing (RS) for forest area monitoring and the use of national forest inventory (NFI) for monitoring forest area, growing stock, biomass, carbon stock, and other attributes in FRA 2005–2020, (b) assess data quality in FRA 2020 using FAO tier-based indicators, and (c) zoom in to investigate changes in tropical forest monitoring capacities in FRA 2010–2020. Globally, the number of countries monitoring forest area using RS at good to very good capacities increased from 55 in FRA 2005 to 99 in FRA 2020. Likewise, the number of countries with good to very good NFI capacities increased from 48 in FRA 2005 to 102 in FRA 2020. This corresponds to ~85% of the global forest area monitored with one or more nationally-produced up-to-date RS products or NFI in FRA 2020. For large proportions of global forests, the highest quality data was used in FRA 2020 for reporting on forest area (93%), growing stock (85%), biomass (76%), and carbon pools (61%). Overall, capacity improvements are more widespread in the tropics, which can be linked to continued international investments for forest monitoring especially in the context of reducing emissions from deforestation and forest degradation in tropical countries (REDD+). More than 50% of the tropical countries with targeted international support improved both RS and NFI capacities in the period 2010–2020 on top of those that already had persistent good to very good capabilities. There is also a link between improvements in national capacities and improved governance measured against worldwide governance indicators (WGI). Our findings—the first global study—suggest an ever-improving data basis for national reporting on forest resources in the context of climate and development commitments, e.g. the Paris Agreement and Sustainable Development Goals.

1. Introduction

Being one of the most biologically rich ecosystems extending over almost one-third of the global land (FAO 2020), forests provide crucial goods and services to the planet and human well-being. Forest resources such as food, fiber, timber, and medicines are the main sources of income and livelihoods for
millions of people in many countries (Vedeld et al 2007, Angelsen et al 2014). Further, forests provide various essential services, e.g. water cycle regulation, soil formation and stabilization, erosion control, to name a few (Martínez Pastur et al 2018). They are also important for aesthetic, spiritual, educational, and recreational purposes (Daniel et al 2012, FAO 2020). On top of these vital benefits, forests have a crucial role in global climate regulation being a source and sink of carbon (Pan et al 2011). Globally, deforestation and forest degradation account for 12%–20% of CO₂ emissions (van der Werf et al 2009, Houghton et al 2012, Friedlingstein et al 2019). At the same time, forests absorb a vast amount of carbon, and over the last decade, the forest carbon sink accounts for about 3.2 Gt CO₂ yr⁻¹ (Friedlingstein et al 2019). If managed sustainably, forests could contribute up to 30% of the Paris Climate Agreement goal towards limiting global warming below 2 °C by 2030 (Griscom et al 2017).

To support climate mitigation and other forest benefits, reliable and systematic monitoring of forests is essential. The Food and Agriculture Organization (FAO) of the United Nations performs Global Forest Resources Assessment (FRA) regularly at the request of and in collaboration with member countries since 1946 (FAO 2020). The most recent assessment, FRA 2020, examines forest resources, their management, and use in 236 countries and territories (FAO 2020). Forest area change and biomass/carbon stock are key variables in FRA, particularly to support countries reporting on ‘Life on Land’ indicators—15.1.1 and 15.2.1 of Sustainable Development Goals (SDGs) (FAO 2020) and the nationally determined contributions (NDCs) to the Paris Agreement adopted at the Conference of the Parties of the United Nations Framework Convention on Climate Change (UNFCCC) in 2015 (IPCC 2006, Herold and Skutsch 2011, Joseph et al 2013, GOFC-GOLD 2016).

Historically, many countries have been producing information on forest area and carbon content using data from forest inventories (Tomppo et al 2010, Goetz et al 2015, GOFC-GOLD 2016, FAO 2018). With the development of satellite imaging and processing technologies, countries have begun to integrate satellite remote sensing (RS) data in their national forest monitoring systems since the early 1980s (FAO 2018). RS data have been used effectively to obtain consistent information about changes in forest area over time (Hansen et al 2009, Pekkarinen et al 2009, Saatchi et al 2011, Hansen et al 2013).

In the global context, variations in data sources and quality can reduce the consistency in forest information among countries. In FRA 2015, countries assessed data quality using Tiers developed by FAO (2015), and ~60% of the global forest cover was reported with the highest quality data (Keenan et al 2015). Two consecutive studies on tropical forest monitoring capacity assessment revealed that the number of tropical countries having good or very good capacities to use RS and national forest inventory (NFI) increased from 37 countries in FRA 2005 to 54 countries in FRA 2015 and from 29 countries in FRA 2005 to 40 countries in FRA 2015, respectively (Romijn et al 2012, 2015).

As tropical forests have a critical role in climate mitigation and maintenance of other ecosystem services, substantial international investments have been channeled to tropical countries to support forest monitoring, particularly in the context of reducing emissions from deforestation and forest degradation in developing countries (REDD+) (UN-REDD 2013, Romijn et al 2015, Kim et al 2019). The Global Forest Observations Initiative (GFOI) provides an inventory of targeted international support to tropical countries for RS and NFI capacity building and helps coordinate activities for REDD+ and related forums (GFOI 2020). Apart from the tropics, a significant share of international support has been provided for temperate forests, particularly in Eastern Europe (McAlpine and Church 2018). Similarly, some countries have invested billions in assessing their forest resources, as notable in forest inventory and analysis in the USA since 1930 (Tinkham et al 2018) and the development of Europe’s 2013 ‘Forest Strategy’ to strengthen sustainable forest management and reduce deforestation in Europe (EC 2018). In this context, it is important to understand how such investments have shaped countries’ forest monitoring capacities over time.

There is also an important connection between forest monitoring and forest governance. Transparency is the backbone of the Paris Agreement. There is a need for enhanced transparency and accountability in the forest and land-use sector through higher-quality, more accessible, and frequently updated information and attention to the institutions and accountability mechanisms that support its responsible use. National governance quality has also been linked to the management of forest resources (Gore et al 2013, Norman et al 2017), and worldwide governance indicators (WGI) influence the protection, restoration, and management of forests in tropical countries (Griscom et al 2020). Forest governance has been central to REDD+ (Van Bodegom et al 2012), and evidence from Brazil, Indonesia, and Guyana—the first recipients of results-based finance—suggests that REDD+ initiatives positively influenced forest governance through increased transparency and public participation (Duchelle et al 2019). Certainly, national governance positively influences forest monitoring capacities or vice versa, but this relationship is still unclear and needs to be further explored.

Until now, national forest monitoring capacities have been studied in the tropics, and significant improvements have been observed (Romijn et al 2012, 2015). However, there exists little...
understanding on how the status and trends in national use of different data sources and their quality (e.g. timeliness) compare globally and whether trends of improving capacities in tropics are persisting. The recent release of FRA 2020 allows updating of this knowledge and assessing the latest status and trends in data sources and quality across the globe. Filling these information gaps is crucial particularly in the context of FRAs and also, for evaluating the progress of global forest-based initiatives such as the Paris Agreement, New York Declaration on Forests, and SDGs, among others.

In this paper, we assess and analyze national forest monitoring capacities and capacity changes globally across 236 countries and territories from FRA 2005, 2010, 2015, and 2020. This is a global analysis that includes all countries and territories covered by FRAs for the first time. Additionally, we zoom into 99 tropical and non-annex 1 countries to the UNFCCC—‘mostly developing countries that are particularly vulnerable to the adverse effects of climate change and/or the implementation of measures to respond to it, because of their specific geographic, climatic, or economic conditions’—to provide a most recent picture on capacity changes in the tropics expanding on the previously published analysis by Romijn et al (2012, 2015). More specifically, we:

(a) analyze forest monitoring data sources used by all countries reporting for the consecutive FRAs in 2005, 2010, 2015, and 2020;
(b) evaluate forest monitoring data quality globally in FRA 2020 using the FAO tier system;
(c) further, zoom in to investigate changes in forest monitoring capacities in 99 non-annex 1 tropical countries.

2. Data and methods
2.1. Data sources for forest monitoring
We assessed national forest monitoring data sources in 236 countries and territories from FRA 2005 to FRA 2020 using the approach developed in previous studies by Romijn et al (2012, 2015). Forest monitoring data sources can be assessed using different criteria. In our study, we first analyzed whether countries derive forest information using RS and/or NFI data sources. After that, we assessed the origin (external/in-country), frequency, and timeliness of these data. To analyze the two main data sources separately, we used separate indicators for RS and NFI data sources, namely ‘Use of RS’, and ‘Use of NFI’. The ‘Use of RS’ is deployed by a country for monitoring its forest area and area change while the ‘Use of NFI’ for deriving forest area and area change, growing stock, biomass, carbon stock, and other forest parameters (FAO 2020). Data sources used in FRA provide an indication of the country capacities to monitor the forests.

Five different criteria were used to rank the indicators between ‘low’ and ‘very good’ data sources for forest monitoring (table 1). ‘Low’ means that countries did not use RS/NFI to derive their forest estimates. Very good use of RS/NFI denotes that countries have their own abilities to monitor forests in a consistent and timely manner using RS/NFI. Limited or intermediate use of RS/NFI means that countries use either partial data or data produced by external sources for forest monitoring. The indicators were scored based on the rank values—from 0 for ‘low’ to 4 for ‘very good’ data sources. Underlying data sources were assessed for the consecutive FRAs in 2005, 2010, 2015, and 2020 and forest monitoring capacity changes were evaluated by comparing FRA 2005 to FRA 2020 data sources.

2.2. Forest monitoring data quality
We assessed forest monitoring data quality in FRA 2020 in 236 countries and territories using FAO’s tier system (table 2). FAO Tiers represent data quality based on Tier 1, Tier 2, and Tier 3 on forest area, growing stock, biomass, and carbon pools (FAO 2020). Tier 3 represents the highest data quality with the most recent and consistent data sources, Tier 2 older, or incomplete data, and Tier 1 the lowest data quality including expert estimates (FAO 2020). The years reported for data quality assessment generally correspond to the years of data collection (as indicated in FRA 2020 guidelines and specifications). The data sources for forest area include either RS or NFI or both while the data are sourced from NFI for growing stock. The status tiers are based on the most recent data point (i.e. RS and/or NFI data in a particular year) while trend tiers look at the existence of multiple data points in time (FAO 2020).

2.3. Analysis of tropical forest monitoring capacity improvements
An additional analysis was conducted in 99 non-annex 1 tropical countries to examine if targeted international support in the tropics contributed to national forest monitoring capacity improvements. Our assessment of forest monitoring data sources was used as a proxy for forest monitoring capacities. Data on the international support for forest monitoring capacity building was compiled from the GFOI inventory of activities. Forty-nine of these tropical countries received targeted support to improve their RS and/or NFI capacities (GFOI 2020). We classified support separately for countries receiving

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5 List of current non-annex 1 countries to the UNFCCC: https://unfccc.int/process/parties-non–party-stakeholders/parties-convention-and-observer-states.
Table 1. Indicator criteria and scores for the data source assessment indicators: Use of RS for forest area monitoring and Use of NFI for forest monitoring in 236 countries and territories in FRA 2005, 2010, 2015, and 2020.

| Indicators for forest area monitoring | Indicator criteria | Indicator value | Indicator score | Data source |
|--------------------------------------|--------------------|----------------|----------------|-------------|
| Use of RS                            | No forest cover map| Low            | 0              | Section 1.2.1 in FRA 2005, FRA 2010, FRA 2015, FRA 2020 country reports |
|                                      | One forest cover map (external) | Limited | 1 | FRA 2015 country reports, section 1 in FRA 2020 country reports |
|                                      | Multiple forest cover maps (external) | Intermediate | 2 | |
|                                      | One or more forest cover map(s) (in-country); most recent produced before 2000 for 2005 assessment, before 2005 for 2010 assessment, before 2010 for 2015 assessment, before 2015 for 2020 assessment | Good | 3 | |
|                                      | Multiple forest cover maps (in-country); most recent produced after 2000 for 2005 assessment, after 2005 for 2010 assessment, after 2010 for 2015 assessment, after 2015 for 2020 assessment | Very good | 4 | |

| Use of NFI for forest monitoring | Indicator criteria | Indicator value | Indicator score | Data source |
|----------------------------------|--------------------|----------------|----------------|-------------|
| Use of NFI                        | No forest inventory| Low            | 0              | Section 5.2.1 in FRA 2005, FRA 2010, FRA 2015, FRA 2020 country reports |
|                                  | One forest inventory (external) | Limited | 1 | |
|                                  | Multiple forest inventories (external); or in-country, but no full cover for all forests | Intermediate | 2 | |
|                                  | One or more forest inventories (in-country); most recent before 2000 for 2005 assessment, before 2005 for 2010 Assessment, before 2010 for 2015 assessment, before 2015 for 2020 assessment | Good | 3 | |
|                                  | Multiple forest inventories (in-country); most recent produced after 2000 for 2005 assessment, after 2005 for 2010 assessment, after 2010 for 2015 assessment, after 2015 for 2020 assessment | Very good | 4 | |

Support for RS and those receiving support for NFI capacity building in order to align it with the capacity (i.e. forest monitoring data sources) indicators. Then, we analyzed capacity changes in countries that received targeted support in comparison to countries without support. As countries started to receive support through GFOI collaborative actions in the 2010s, capacity changes were analyzed over the period from 2010 to 2020. The capacity changes were analyzed in three groups: very good capacity throughout the period, capacity improvements, and no capacity improvements. Here, no capacity improvements do not necessarily mean low capacities. For example, a country can have good capacities but did not improve to very good capacities over the period examined.

The RS and NFI capacity changes in 99 countries were further investigated in the abovementioned three groups in relation to the quality of country governance from 2010 to 2020. We performed the Kruskal–Wallis test to explore if there is a difference in WGI trend between three groups for both RS and NFI capacity changes. This test was selected as the WGI trend was not normally distributed. We used the World Bank governance indicators (WGI) for this analysis since they are the most widely used indicators across the countries since 1996 (Kaufmann and Kraay 2019). The WGI comprises six indicators summarizing the quality of governance: voice and accountability, political stability and absence of violence/terrorism, government effectiveness, regulatory quality, rule of law, and control of corruption. WGI ranges from $-2.5$ (weak governance) to 2.5 (strong governance) (Kaufmann and Kraay 2019).

3. Results

3.1. Data sources for forest monitoring

Figure 1 and table 3 show that both the use of RS and NFI for forest monitoring improved significantly across the globe between FRA 2005 and FRA 2020 (see appendix A for indicator values in all countries). Out of 236, 99 countries demonstrated good to very good use of RS in FRA 2020 (table 3). This represented an 80% increase in the number of countries capable to produce in-country forest cover maps using RS compared to FRA 2005. Furthermore, countries with good to very good use of NFI more than doubled over the period from 48 countries in FRA 2005 to 102 countries in FRA 2020. The improvements were also reflected in the amount of forest cover monitored with improved data sources over the period (figure 2).
Table 2. FAO tier indicators used in the assessment of forest monitoring data quality.

| Tier indicators | Indicator criteria                                                                 | Indicator value | Data source                              |
|-----------------|------------------------------------------------------------------------------------|-----------------|------------------------------------------|
| Forest area     | Status: Data from 2013 or more recent from a good data source (NFIs, sample-based RS, wall-to-wall mapping) | Tier 3          | Section 1 in FRA 2020 country reports    |
|                 | Data older than 2013 and good data source                                          | Tier 2          |                                          |
|                 | Other (incl. data from registers or questionnaires, expert assessments)            | Tier 1          |                                          |
| Trend           | Multiple consistent data points (in terms of methods and classes), all from 2013 or more recent or Tier 3 Status, incl. recent forest area change estimates (i.e. from a REDD+ FREL) | Tier 3          |                                          |
|                 | Multiple data points but limited consistency (in terms of methods and classes), and/or older than 2013, incl. 1 data point and expanded trends from the external data source | Tier 2          |                                          |
|                 | Other                                                                              | Tier 1          |                                          |
| Growing Stock   | Status: Data from NFIs from 2009 or more recent (incl. RS-based method calibrated by inventory plot data) | Tier 3          | Section 2 in FRA 2020 country reports    |
|                 | Data from NFIs older than 2009                                                      | Tier 2          |                                          |
|                 | Other                                                                              | Tier 1          |                                          |
| Trend           | Data from multiple consistent NFIs, all from 2009 or more recent                  | Tier 3          |                                          |
|                 | Data from multiple NFIs or RS-based estimates but limited consistency, and/or older than 2009, incl. cases with one NFI and using detailed multi-date RS assessment of different forest types | Tier 2          |                                          |
|                 | Other                                                                              | Tier 1          |                                          |
| Biomass*        | Data derived from country-specific or targeted expansion factors, allometric models, etc. | Tier 3          | Section 2c in FRA 2020 country reports   |
|                 | Data derived from default factors or generic equations, i.e. all countries using the biomass calculator | Tier 1          |                                          |
| Carbon pools    | Data provided for all five carbon pools (AGB, BGB, litter, deadwood, and soil)     | Tier 3          | Section 2d in FRA 2020 country reports   |
|                 | Data provided for at least two carbon pools                                        | Tier 2          |                                          |
|                 | Other                                                                              | Tier 1          |                                          |

* Only Tier 1 and Tier 3 are considered in the case of biomass indicator.

The proportion of global forest cover monitored with good to very good use of RS increased from 69% (2848 million ha) in FRA 2005 to 84% (3406 million ha) in FRA 2020. The corresponding figure for use of NFI increased from 55% (2280 million ha) in FRA 2005 to 85% (3462 million ha) in FRA 2020.

Noticeably, the greatest improvements took place in tropical countries where the good to very good use of RS and NFI increased from 35 and 21 countries in FRA 2005 to 69 and 57 countries in FRA 2020, respectively (figure 1 and table B1.1 in appendix B). Specifically, tropical countries significantly improved their use of NFI between FRA 2015 and FRA 2020 (see also figure 2). Further zooming in revealed that improvements are more pronounced in African countries where capacities to produce in-country RS maps and NFIs rose to 31 and 27 countries respectively in FRA 2020, from 8 countries in each case in FRA 2005 (table B1.2). Similarly, capacities improved in South America where seven countries were able to produce in-country NFIs in 2020 compared to two countries in FRA 2005 (table B1.7). Overall, most of the countries in Asia, Oceania, and South America had very good use of RS (tables B1.3, B1.6 and B1.7) while the USA and Canada had very good use of NFIs throughout the period (figure 1). A substantial improvement also occurred in Europe where the number of countries with consistent time series of in-country NFIs more than doubled over the period (table B1.4).

Between FRA 2005 and FRA 2020, the number of countries with low use of RS and NFI went down globally by 31% and 33%, respectively (table 3). The number of countries using partial or external RS data (limited and intermediate use) remained stable, while the number of countries with limited and intermediate use of NFI decreased by 20%. Overall, the decline in RS and NFI deployment only took place in very few countries. Specifically, the RS use in Costa Rica and Panama, and the NFI use in Kyrgyzstan and the Philippines fell from
Figure 1. Use of data sources for forest monitoring and changes in 236 countries and territories from FRA 2005 to FRA 2020: use of RS for forest area monitoring in FRA 2005 (1a), FRA 2020 (1b), and changes in the use of RS (1c); use of NFI for forest monitoring in FRA 2005 (2a), FRA 2020 (2b), and changes in the use of NFI (2c).

Table 3. The number of countries by data source indicator value for ‘Use of RS’ and ‘Use of NFI’ in FRA 2005, 2010, 2015, and 2020 (n = 236).

| Data source indicator value | Use of RS for forest area monitoring | Use of NFI for forest monitoring |
|-----------------------------|--------------------------------------|----------------------------------|
|                             | 2005 | 2010 | 2015 | 2020 | 2005 | 2010 | 2015 | 2020 |
| Very good                   | 23   | 22   | 36   | 53   | 20   | 24   | 32   | 41   |
| Good                        | 32   | 44   | 44   | 46   | 28   | 40   | 45   | 61   |
| Intermediate                | 25   | 26   | 23   | 24   | 21   | 29   | 34   | 34   |
| Limited                     | 22   | 24   | 23   | 22   | 39   | 36   | 24   | 14   |
| Low                         | 134  | 120  | 110  | 91   | 128  | 107  | 101  | 86   |

very good to good over the period (figures 1(c) and 2(c)). The reason for this decline is that countries did not regularly update data which made the data sources too old to be labeled as very good in FRA 2020.

Figure 3 shows that most of the countries used recent data for forest monitoring. Out of 145, 104 countries used RS data produced in the 2010s including 70 countries using data produced since 2015. Regarding NFI, 94 countries used data produced in the 2010s and 62 countries from 2015. Notably, many countries in the (sub)tropics used recent data: 91 and 62 countries used the RS and NFI data respectively produced in the last 10 years. Among them, 59 countries had RS data, and 40 countries NFI data, produced since 2015. Also, several temperate countries used recent NFI data—26 countries using data from the 2010s and 20 countries from 2015 onwards. Comparing the two graphs in figure 3 demonstrates that RS-based data sources are more recent than those for NFIs. This reflects that countries are able to produce more frequent and recent RS-based estimations while NFIs take some time to complete and keep up to date for reporting. Although the use of recent data was notable, temporal frequency varied between 5 and 10 years in most of the countries with multi-date data.

3.2. Data quality assessment in FRA 2020

The data quality results show that more than half of the countries (53%) used the highest quality data (i.e. Tier 3 data) for reporting forest area status in FRA 2020 covering ~93% of the global forest cover (table 4). However, the number of countries using
Tier 3 data is relatively smaller for growing stock status, followed by biomass and carbon pool. Furthermore, comparatively fewer countries used the highest quality data for trend estimations. When it comes to biomass, just a quarter of the countries used Tier 3 data but covered about three-quarters of the global forests, and among them, six countries viz. Australia, Brazil, Canada, China, Russia, and the USA covered more than 57% of the forests (>2 billion ha). For reporting carbon pool, only ~19% of the countries used Tier 3 data, while it covered nearly 61% of the global forests and out of it, Australia, Brazil, Canada, Russia, and the USA covered around 52% of the forests.

In general, most of the countries in Western Europe, and North and Central America used Tier 3 data for forest monitoring, followed by Asia and South America, whereas African countries mostly used Tier 1/Tier 2 data (figure 4). Especially for measuring trends, biomass, and carbon pool, most of the African countries used lower quality data. Many countries in Asia, Eastern Europe, and South America also used lower quality data for biomass and carbon pool measurements. On the other hand, some countries including Australia did not report growing stock; these countries cover ~4% of the global forests. The forest coverage with no data was <1% for both biomass and carbon pool.

3.3. Analysis of tropical forest monitoring capacity improvements
Capacity improvements are higher in the tropical countries receiving direct, targeted support for forest monitoring compared to tropical countries without such support (table 5). More than 50% of the countries with targeted support for both RS and NFI improved their capacities on top of those with good and very good capabilities over the period. In contrast, some 45% of the countries showed no capacity
improvements both for RS and NFI in the absence of dedicated support. Still, 40% of the countries without support improved their RS capacities, and 34% improved NFI capacities. There is a small share of countries (16%) that received support but did not improve their RS capacities, and this figure was almost double for NFI. The reason could be that fieldwork, data analysis, and reporting on NFIs take longer, and some countries initiated NFIs with support, but they did not yet complete them and report on the estimations.

Our study further revealed a link between forest monitoring capacity improvements and improving governance trends (as defined by WGI) in tropical countries (figure 5). Regarding both RS and NFI, countries with very good capacities throughout the study period, and countries with capacity improvements, were found to have comparatively higher-quality governance trends than countries with no capacity improvements. In particular, very good NFI capacities were found in countries with much higher governance trends compared to very good RS capacities. About 75% of the countries with very good RS capacities had governance trends above zero whereas all countries with very good NFI capacities had positive governance trends. However, no significant differences between the groups were found.

4. Discussion

Overall, our findings show a trajectory towards improvement in forest monitoring capacities
Table 5. Forest monitoring capacity improvements with and without targeted international support for RS and NFI in 99 non-Annex 1 tropical countries from FRA 2010 to FRA 2020. The analysis was based on support reported in the GFOI inventory of activities. There might be more countries with support not reported in the GFOI inventory of activities.

| Capacity improvement group | Forest area change monitoring and RS capacities | NFI capacities |
|----------------------------|-----------------------------------------------|----------------|
|                            | Countries with support (n = 49) | Countries without support (n = 50) | Countries with support (n = 43) | Countries without support (n = 56) |
| ‘Good and very good’ capacities throughout the period | 29% | 16% | 19% | 21% |
| Capacity improvements | 55% | 40% | 51% | 34% |
| No capacity improvements (including decline) | 16% | 44% | 30% | 45% |

Figure 5. Forest area monitoring and RS capacity improvements, $H = 4.6, p = 0.10$ (a), and NFI capacity improvements, $H = 5.5, p = 0.06$ (b) relating to WGI trend from 2010 to 2020. Capacities are grouped into very good capacities throughout the period, capacity improvement, and no improvement from FRA 2010 to 2020.

worldwide. Improvements are especially promising in tropical countries where the use of RS at good to very good levels improved by $\sim 49\%$ between FRA 2005 and FRA 2015. The use of NFI improved even more ($\sim 71\%$) in the same period. From FRA 2015 onwards, the tropics have seen substantial improvements; the numbers of countries with good to very good use of RS and NFI increased by $\sim 33\%$ and $\sim 58\%$ respectively. These findings reassert a continuation in the trends of capacity improvements in the tropics observed by Romijn et al. (2015). Significant improvements have also been observed in monitoring temperate and boreal forests mostly using NFIs at good to very good levels.

Our results confirm the previous findings by Romijn et al. (2015) that capacity improvements in tropical countries can be linked to international investments, and show that these improvements persist. More specifically, the RS and NFI capacity improvements with international support in the majority of the tropical countries emphasize the positive effects of dedicated RS and NFI capacity development activities. This is further supported by the result that a large fraction of countries showed no capacity improvements in the absence of international support, emphasizing the need for continuation and amplification of such investments in the coming years. Nonetheless, the question warrants further research as the existence of tropical countries with dedicated support but no improvements indicating the possibility that other factors affect capacity developments in these countries. Capacity improvements in tropical countries with or without external support are in particular due to investments in forest monitoring motivated by national and international climate agendas such as results-based payments under the REDD+ mechanism. Other possible reasons could be an increase in technology transfer through online material and documentation, and experience sharing among countries.

The observation of a link between forest monitoring capacity improvements and improvements in governance trends in the tropics is not surprising, given that good governance has been linked to better forest management (Griscom et al. 2020). The results that persisting very good NFI capacities...
in countries with much higher governance trends compared to very good RS capacities indicate that increasing good governance in countries favor the implementation of fieldwork required for completing the field inventories for NFI and updating them regularly. We suggest international support for tropical forest monitoring should be linked to efforts for overall governance improvements to promote enhanced transparency and accountability among countries for continuing and maintaining capacity improvements, more prominently NFI capacities.

Despite significant capacity improvements in the tropics, a consistent time series of in-country RS data is still rare in Africa and parts of Asia. A consistent time series of in-country NFIs is even rarer in Africa, parts of Asia, and South America. In some countries, capacities have not improved in spite of receiving international support, and this share of countries is much higher for NFI. This may be due to the longer time that it takes for completing field inventories needed in NFI (McRoberts and Tomppo 2007, Wittke et al 2019). In addition, forest monitoring in many tropical countries is currently based on either partial, external, or very old data and the amount of forest cover monitored with these data is comparatively higher for NFI (773 million ha). All these findings suggest that further efforts are needed to improve capacities in tropical countries, with emphasis on providing updated NFI-type information more frequently.

Globally, reporting on ~85% of the forest cover is now based on nationally derived RS or NFI data. A striking methodological difference is observed in forest monitoring between Northern and Southern countries. Tropical countries mainly use RS data, while Europe and the USA predominantly rely on NFI data. This tendency could be linked to the origin of forest inventories in Europe and the USA in timber resource assessments which later gave rise to their broader use for sustainable forest management (Lorenz and Fischer 2013, Tkacz et al 2013). This also reflects the availability of the resources in these countries to sustain the NFI system for forest monitoring and partially, the importance of the forest sectors in the national economy in some of these countries.

In terms of temporal frequency in forest monitoring, variations between 5 and 10 years were observed in most of the countries. Thus, current country reporting does not provide global data at annual/biannual time steps. Satellite RS data would allow more frequent reporting on some attributes because it provides observations at a higher temporal frequency which can be used for monitoring forest dynamics such as tree cover loss, deforestation, and forest fires (Setiawan et al 2015, Tang et al 2019). While NFIs take significant time to complete, integrating frequent RS observations with NFIs could help increase reporting frequency on tree cover, forest area, biomass, and their changes, anticipating more frequent reporting needs in the future under the Paris Agreement and the SDGs.

Globally, more than half of the countries now use Tier 3 data for reporting forest area status covering ~93% of the forests, which reveals a 33% increase from 2015 compared with the findings by Keenan et al (2015). However, nearly two-thirds of the countries worldwide report biomass using Tier 1 data which is linked to the use of default biomass conversion factors due to lack of NFIs particularly in Africa, parts of Asia and South America, and Eastern Europe. However, some tropical countries use the default biomass conversion factors despite having NFIs, be it for convenience or because they have not started to use country-specific factors since NFIs are recent. Also, ~80% of the world countries report carbon pool using Tier 2 data, i.e. these countries are not producing deadwood, litter, and soil-related carbon data. This is because these parameters are not fully measurable without an NFI (Pearson et al 2014). In some cases, tropical countries report biomass/carbon pool using lower quality data to international reporting, despite having the highest quality data available, such as in Indonesia. Such limits in reporting capacities suggest that international support should be provided not only to enhance forest monitoring capacities but to be continued until countries have built capacities for high-quality international reporting as well.

The quality of forest monitoring data in our study was measured in terms of age and nature of the data. We did not investigate if countries used temporary or permanent field plots in case of multiple NFIs nor do we explicitly differentiate between forest inventories and logging inventories as this information was not consistently available across all countries. As these variations in NFIs can influence data quality, they could be considered in a more detailed analysis. Furthermore, diversity in NFIs can lead to variations in data quality across countries (Vidal et al 2016). Field sampling and analytical methods have been reported to result in varying estimates in European forests (Clarke et al 2011). Such data variations across Europe led to the establishment of the European NFI Network in 2003 to enhance data harmonization for international comparisons, which could be a benchmark to start data harmonization in other countries (Vidal et al 2016). Also, sources of variations could be integrated into the FRA data quality assessment to enhance data harmonization across the globe. Additionally, data latency can also affect data quality and timely reporting of forest information to national and international platforms. Therefore, reducing higher data latency particularly in NFI could be an important objective in future forest monitoring capacity building initiatives.
5. Conclusions

This study shows substantial improvements in national forest monitoring capacities around the globe. Forest area monitoring using RS at good to very good levels increased from 55 countries in FRA 2005 to 99 in FRA 2020. The number of countries with good to very good use of NFI rose from 48 in FRA 2005 to 102 in FRA 2020. These figures correspond to more than 3.4 billion ha (~85%) global forest cover monitored with good to very good use of RS or NFI data in FRA 2020. The use of RS is not expected to increase in the Northern countries including Europe and the USA since they mostly use NFIs as main data sources to report on forests. While the use of RS is more widespread in the Southern countries (tropics), the use of multi-date RS is rare, especially in Africa. In addition, there are still several tropical countries particularly in Africa, and Western and Central Asia where the use of RS is low. Tropical countries have recently started to implement NFIs, but multi-date NFIs remain rarer particularly in Africa and parts of Asia and South America. Globally, 53% of the countries now use the highest quality data for reporting forest area status covering ~93% of the forest cover. However, the use of the highest quality data is lower for monitoring growing stock, biomass, and carbon pools in Africa, parts of Asia and South America, and East Europe. Therefore, greater efforts should be made in these regions to enable countries to implement NFI which will also help to improve data quality especially biomass and carbon pool that depends on NFI data.

More than 50% of countries receiving dedicated external financial support improved both their RS and NFI capacities, apart from those with already very good capacities throughout the period. However, several countries that received support have not improved capacities, and this proportion is higher for NFI. Our study further reveals a positive link between improved forest monitoring capacities and improvement on indicators of good governance, and this link is more pronounced for NFI. These results suggest that it could be advantageous to combine international support for forest monitoring with governance improvements in tropical countries to better advance national forest monitoring capacities, more prominently NFI capacities. However, further investigation is needed to reveal how country governance or other factors affect forest monitoring capacities.

This study is the first investigation of the status and trends in global data sources and forest monitoring capacities between FRA 2005 and FRA 2020, and an analysis of forest monitoring data quality in FRA 2020. Thus, it offers the information required to evaluate the need for further efforts in improving national capacities in using RS and NFI data sources and data quality in the context of evaluating the progress of global forest-based climate change mitigation and development initiatives. In addition, the findings are useful for donors and policymakers to decide where to direct further support for improving forest monitoring capacities.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: http://lucid.wur.nl/datasets/forest-monitoring-capacities.

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Disclaimer

The designations employed and the presentation of the material in the maps do not imply the expression of any opinion whatsoever on the part of the authors concerning the legal or constitutional status of any country, territory or sea area, or concerning the delimitation of frontiers.

Appendix A. Data source assessment scores for all countries

This appendix contains the indicator scores for the data source assessment indicators: Use of RS for forest area monitoring and Use of NFI for forest monitoring for 236 countries and territories in FRA 2005–2020. The scores correspond to the indicator values (table 1) where 0 represents low, 1 limited; 2 intermediate, 3 good, and 4 very good use of data sources.
| Country                      | Use of RS for forest area monitoring | Use of NFI for forest monitoring |
|------------------------------|-------------------------------------|----------------------------------|
|                              | 2005  | 2010  | 2015  | 2020  | 2005  | 2010  | 2015  | 2020  |
| Afghanistan                  | 1     | 1     | 1     | 2     | 0     | 0     | 0     | 0     |
| Albania                      | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0     |
| Algeria                      | 0     | 0     | 0     | 0     | 3     | 3     | 3     | 3     |
| American Samoa               | 2     | 2     | 2     | 2     | 1     | 1     | 1     | 1     |
| Andorra                      | 3     | 3     | 3     | 3     | 0     | 0     | 0     | 0     |
| Angola                       | 0     | 0     | 0     | 4     | 1     | 1     | 1     | 3     |
| Anguilla                     | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0     |
| Antigua and Barbuda          | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0     |
| Argentina                    | 3     | 3     | 4     | 4     | 3     | 3     | 4     | 4     |
| Armenia                      | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0     |
| Aruba                        | 2     | 2     | 2     | 2     | 0     | 0     | 0     | 0     |
| Australia                    | 4     | 4     | 4     | 4     | 2     | 2     | 2     | 2     |
| Austria                      | 0     | 0     | 0     | 4     | 3     | 3     | 3     | 4     |
| Azerbaijan                   | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0     |
| Bahamas                      | 0     | 0     | 0     | 0     | 1     | 1     | 1     | 1     |
| Bahrain                      | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0     |
| Bangladesh                   | 1     | 3     | 4     | 4     | 3     | 3     | 3     | 4     |
| Barbados                     | 0     | 1     | 1     | 1     | 0     | 0     | 0     | 0     |
| Belarus                      | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0     |
| Belgium                      | 0     | 0     | 0     | 0     | 2     | 2     | 2     | 2     |
| Belize                       | 0     | 2     | 2     | 2     | 0     | 1     | 1     | 1     |
| Benin                        | 1     | 1     | 2     | 3     | 0     | 3     | 3     | 3     |
| Bermuda                      | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0     |
| Bhutan                       | 2     | 2     | 3     | 4     | 1     | 1     | 1     | 3     |
| Bolivia (Plurinational State of) | 4   | 4     | 4     | 4     | 2     | 2     | 2     | 2     |
| Bonaire, Sint Eustatius and Saba | 1   | 1     | 1     | 2     | 1     | 1     | 1     | 0     |
| Bosnia and Herzegovina       | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0     |
| Botswana                     | 1     | 2     | 2     | 3     | 1     | 1     | 1     | 3     |
| Brazil                       | 4     | 4     | 4     | 4     | 2     | 2     | 2     | 3     |
| British Virgin Islands       | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0     |
| Brunei Darussalam            | 3     | 3     | 3     | 3     | 2     | 2     | 2     | 2     |
| Bulgaria                     | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0     |
| Burkina Faso                 | 0     | 0     | 1     | 3     | 2     | 2     | 2     | 3     |
| Burundi                      | 1     | 1     | 1     | 1     | 0     | 2     | 2     | 2     |
| Cabo Verde                   | 0     | 0     | 0     | 0     | 1     | 1     | 3     | 3     |
| Cambodia                     | 3     | 3     | 3     | 4     | 1     | 1     | 1     | 1     |
| Cameroon                     | 2     | 2     | 2     | 2     | 3     | 3     | 3     | 3     |
| Canada                       | 4     | 4     | 4     | 4     | 4     | 4     | 4     | 4     |
| Cayman Islands               | 0     | 3     | 3     | 3     | 0     | 0     | 0     | 0     |
| Central African Republic     | 0     | 0     | 1     | 1     | 1     | 1     | 1     | 1     |
| Chad                         | 0     | 0     | 0     | 0     | 2     | 2     | 2     | 2     |
| Chile                        | 4     | 4     | 4     | 4     | 3     | 3     | 3     | 4     |
| China                        | 4     | 4     | 4     | 4     | 4     | 4     | 4     | 4     |
| Colombia                     | 4     | 4     | 4     | 4     | 0     | 1     | 3     | 4     |
| Comoros                      | 0     | 0     | 0     | 0     | 0     | 0     | 3     | 3     |
| Congo                        | 3     | 3     | 3     | 3     | 0     | 0     | 3     | 4     |
| Cook Islands                 | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0     |
| Costa Rica                   | 4     | 3     | 3     | 3     | 1     | 1     | 3     | 3     |
| Cote d’Ivoire                | 2     | 3     | 3     | 4     | 0     | 0     | 0     | 3     |
| Croatia                      | 3     | 4     | 4     | 4     | 0     | 0     | 0     | 0     |
| Cuba                         | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0     |
| Curacao                      | 1     | 1     | 1     | 1     | 1     | 1     | 1     | 1     |
| Cyprus                       | 3     | 3     | 3     | 3     | 0     | 0     | 0     | 0     |
| Czechia                      | 0     | 0     | 0     | 0     | 0     | 3     | 3     | 4     |
| Democratic People's Republic of Korea | 0   | 0     | 0     | 2     | 0     | 0     | 0     | 0     |
| Democratic Republic of the Congo | 2   | 3     | 3     | 3     | 1     | 2     | 2     | 3     |
| Denmark                      | 0     | 0     | 3     | 3     | 0     | 3     | 4     | 4     |
| Djibouti                     | 1     | 1     | 1     | 1     | 0     | 0     | 0     | 0     |
| Dominica                     | 2     | 2     | 2     | 2     | 0     | 0     | 0     | 0     |
| Dominican Republic           | 0     | 3     | 3     | 3     | 0     | 0     | 0     | 3     |

(Continued)
| Country                          | Use of RS for forest area monitoring | Use of NFI for forest monitoring |
|---------------------------------|-------------------------------------|----------------------------------|
|                                 | 2005  | 2010  | 2015  | 2020  | 2005  | 2010  | 2015  | 2020  |
| Ecuador                         | 3     | 3     | 4     | 4     | 0     | 0     | 3     | 3     |
| Egypt                           | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0     |
| El Salvador                     | 3     | 3     | 3     | 3     | 0     | 0     | 3     | 3     |
| Equatorial Guinea               | 0     | 0     | 0     | 3     | 1     | 1     | 1     | 1     |
| Eritrea                         | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0     |
| Estonia                         | 0     | 0     | 0     | 0     | 3     | 4     | 4     | 4     |
| Eswatini                        | 3     | 3     | 3     | 3     | 3     | 3     | 3     | 3     |
| Ethiopia                        | 3     | 3     | 3     | 3     | 3     | 3     | 3     | 3     |
| Falkland Islands (Malvinas)     | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0     |
| Faroe Islands                   | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0     |
| Fiji                            | 0     | 0     | 0     | 0     | 2     | 3     | 3     | 3     |
| Finland                         | 0     | 0     | 0     | 0     | 4     | 4     | 4     | 4     |
| France                          | 0     | 0     | 0     | 0     | 4     | 4     | 4     | 4     |
| French Guyana                   | 2     | 2     | 2     | 2     | 2     | 2     | 2     | 2     |
| French Polynesia                | 0     | 0     | 0     | 2     | 0     | 0     | 0     | 0     |
| Gabon                           | 0     | 0     | 0     | 3     | 1     | 1     | 1     | 1     |
| Gambia                          | 1     | 1     | 1     | 3     | 1     | 1     | 3     | 3     |
| Georgia                         | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0     |
| Germany                         | 0     | 0     | 0     | 0     | 4     | 4     | 4     | 4     |
| Ghana                           | 3     | 3     | 3     | 4     | 1     | 2     | 2     | 2     |
| Gibraltar                       | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0     |
| Greece                          | 0     | 0     | 0     | 0     | 1     | 1     | 1     | 1     |
| Greenland                       | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0     |
| Grenada                         | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0     |
| Guadeloupe                      | 0     | 0     | 0     | 2     | 0     | 0     | 0     | 0     |
| Guam                            | 2     | 2     | 2     | 2     | 1     | 1     | 1     | 2     |
| Guatemala                       | 4     | 4     | 4     | 4     | 3     | 3     | 3     | 3     |
| Guernsey                        | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0     |
| Guinea                          | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0     |
| Guinea-Bissau                   | 2     | 2     | 2     | 2     | 0     | 0     | 0     | 0     |
| Guyana                          | 0     | 0     | 0     | 4     | 0     | 1     | 2     | 2     |
| Haiti                           | 0     | 0     | 0     | 4     | 0     | 0     | 0     | 0     |
| Holy See                        | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0     |
| Honduras                        | 0     | 0     | 0     | 4     | 0     | 0     | 0     | 0     |
| Hungary                         | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0     |
| Iceland                         | 0     | 0     | 4     | 3     | 0     | 3     | 3     | 4     |
| India                           | 4     | 4     | 4     | 4     | 4     | 4     | 4     | 4     |
| Indonesia                       | 4     | 4     | 4     | 4     | 3     | 3     | 4     | 4     |
| Iran (Islamic Republic of)      | 4     | 3     | 4     | 4     | 2     | 3     | 3     | 3     |
| Iraq                            | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0     |
| Ireland                         | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0     |
| Isle of Man                     | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0     |
| Israel                          | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0     |
| Italy                           | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0     |
| Jamaica                         | 3     | 3     | 3     | 3     | 1     | 1     | 2     | 2     |
| Japan                           | 4     | 4     | 4     | 4     | 4     | 4     | 4     | 4     |
| Jersey                          | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0     |
| Jordan                          | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0     |
| Kazakhstan                      | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0     |
| Kenya                           | 0     | 0     | 4     | 4     | 1     | 2     | 2     | 2     |
| Kiribati                        | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0     |
| Kuwait                          | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0     |
| Kyrgyzstan                      | 4     | 4     | 3     | 4     | 4     | 4     | 3     | 3     |
| Lao People's Democratic Republic| 3     | 3     | 3     | 4     | 3     | 3     | 3     | 3     |
| Latvia                          | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0     |
| Lebanon                         | 3     | 3     | 3     | 4     | 3     | 3     | 3     | 3     |
| Lesotho                         | 2     | 2     | 2     | 2     | 0     | 0     | 0     | 0     |
| Liberia                         | 2     | 2     | 2     | 2     | 0     | 0     | 0     | 0     |
| Libya                           | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0     |
| Liechtenstein                   | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0     |
| Country                           | Use of RS for forest area monitoring | Use of NFI for forest monitoring |
|----------------------------------|-------------------------------------|---------------------------------|
|                                  | 2005 10 15 2020                     | 2005 10 15 2020                  |
| Lithuania                        | 0 0 0 0                            | 0 3 4 4                          |
| Luxembourg                       | 0 0 0 0                            | 3 3 3 3                          |
| Madagascar                       | 2 2 3 3                            | 3 3 3 3                          |
| Malawi                           | 1 1 2 3                            | 1 1 1 3                          |
| Malaysia                         | 4 4 4 4                            | 3 4 4 3                          |
| Maldives                         | 0 0 0 0                            | 0 0 0 0                          |
| Mali                             | 0 0 0 0                            | 2 2 2 2                          |
| Malta                            | 1 1 1 1                            | 0 0 0 0                          |
| Marshall Islands                 | 0 1 1 1                            | 0 1 1 1                          |
| Martinique                       | 0 0 0 2                            | 0 0 0 0                          |
| Mauritania                       | 0 0 0 1                            | 1 1 1 2                          |
| Mauritius                        | 0 0 0 0                            | 0 0 0 0                          |
| Mayotte                          | 0 3 3 4                            | 0 0 0 0                          |
| Mexico                           | 4 4 4 4                            | 4 4 4 4                          |
| Micronesia (Federated States of) | 0 1 1 1                            | 1 2 2 2                          |
| Monaco                           | 0 0 0 0                            | 0 0 0 0                          |
| Mongolia                         | 0 0 0 4                            | 0 0 0 3                          |
| Montenegro                       | 2 2 2 2                            | 0 1 3 3                          |
| Montserrat                       | 0 0 0 1                            | 0 0 0 0                          |
| Morocco                          | 3 3 4 3                            | 3 3 4 3                          |
| Mozambique                       | 2 2 2 3                            | 1 1 1 3                          |
| Myanmar                          | 4 4 4 4                            | 3 3 3 3                          |
| Namibia                          | 1 2 2 2                            | 3 3 3 3                          |
| Nauru                            | 0 0 0 0                            | 0 0 0 0                          |
| Nepal                            | 3 3 3 3                            | 3 3 3 3                          |
| Netherlands                      | 3 3 3 3                            | 4 4 4 4                          |
| New Caledonia                    | 0 3 3 3                            | 1 1 1 1                          |
| New Zealand                      | 4 4 4 4                            | 4 4 4 4                          |
| Nicaragua                        | 3 3 3 4                            | 1 3 3 3                          |
| Niger                            | 0 0 0 0                            | 2 2 2 2                          |
| Nigeria                          | 0 0 0 3                            | 1 1 1 3                          |
| Niue                             | 0 0 0 0                            | 0 3 3 3                          |
| Norfolk Island                   | 0 0 0 0                            | 0 0 0 0                          |
| North Macedonia                  | 0 0 0 0                            | 0 0 0 0                          |
| Northern Mariana Islands         | 2 2 2 2                            | 1 1 1 2                          |
| Norway                           | 0 0 0 0                            | 4 4 4 4                          |
| Oman                             | 0 0 0 0                            | 0 0 0 3                          |
| Pakistan                         | 0 0 1 4                            | 1 1 1 3                          |
| Palau                            | 2 2 2 2                            | 1 2 2 2                          |
| Palestine                        | 0 0 0 0                            | 0 0 0 0                          |
| Panama                           | 4 4 4 3                            | 2 2 2 3                          |
| Papua New Guinea                 | 2 2 3 4                            | 2 2 2 2                          |
| Paraguay                         | 2 2 3 4                            | 0 0 0 3                          |
| Peru                             | 4 3 4 4                            | 0 0 0 3                          |
| Philippines                      | 0 3 4 4                            | 4 3 3 3                          |
| Pitcairn                         | 0 0 0 0                            | 0 0 0 0                          |
| Poland                           | 0 0 0 0                            | 0 0 0 4                          |
| Portugal                         | 0 0 0 0                            | 4 4 4 4                          |
| Puerto Rico                      | 0 0 0 0                            | 2 2 2 2                          |
| Qatar                            | 0 0 0 0                            | 0 0 0 0                          |
| Republic of Korea                | 4 4 4 4                            | 4 4 4 4                          |
| Republic of Moldova              | 0 0 0 0                            | 0 0 0 0                          |
| Reunion                          | 0 0 0 2                            | 0 0 0 0                          |
| Romania                          | 0 0 0 0                            | 3 3 3 3                          |
| Russian Federation               | 4 4 4 4                            | 4 4 4 4                          |
| Rwanda                           | 0 0 3 3                            | 3 3 3 3                          |
| Saint-Martin (French Part)       | 0 0 0 1                            | 0 0 0 0                          |
| Saint Barthelemy                 | 0 0 0 1                            | 0 0 0 0                          |
| Saint Helena, Ascension and Tristan da Cunha | 0 0 0 0 | 0 0 0 0 |
| Saint Kitts and Nevis            | 0 1 1 1                            | 0 0 0 0                          |

(Continued)
| Country                         | Use of RS for forest area monitoring | Use of NFI for forest monitoring |
|--------------------------------|-------------------------------------|----------------------------------|
|                                | 2005 | 2010 | 2015 | 2020 | 2005 | 2010 | 2015 | 2020 |
| Saint Lucia                    | 2    | 2    | 2    | 3    | 2    | 2    | 2    | 2    |
| Saint Pierre and Miquelon      | 1    | 1    | 2    | 2    | 0    | 0    | 0    | 2    |
| Saint Vincent and the Grenadines | 0    | 1    | 1    | 1    | 3    | 3    | 3    | 3    |
| Saoa                           | 3    | 3    | 3    | 3    | 0    | 0    | 0    | 3    |
| San Marino                     | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    |
| Sao Tome and Principe          | 0    | 0    | 0    | 0    | 1    | 1    | 2    | 2    |
| Saudi Arabia                   | 0    | 3    | 3    | 3    | 0    | 3    | 3    | 3    |
| Senegal                        | 3    | 3    | 3    | 4    | 3    | 3    | 3    | 3    |
| Serbia                         | 0    | 0    | 0    | 0    | 0    | 3    | 3    | 3    |
| Seychelles                     | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    |
| Sierra Leone                   | 2    | 2    | 2    | 2    | 0    | 0    | 0    | 0    |
| Singapore                      | 0    | 0    | 1    | 4    | 0    | 0    | 0    | 4    |
| Sint Maarten (Dutch part)      | 1    | 1    | 1    | 1    | 1    | 1    | 1    | 1    |
| Slovakia                       | 0    | 0    | 0    | 0    | 2    | 3    | 3    | 4    |
| Slovenia                       | 3    | 4    | 4    | 4    | 3    | 4    | 4    | 4    |
| Solomon Islands                | 0    | 0    | 0    | 0    | 0    | 2    | 2    | 2    |
| Somalia                        | 1    | 1    | 1    | 1    | 0    | 0    | 0    | 0    |
| South Africa                   | 3    | 3    | 3    | 4    | 0    | 0    | 0    | 0    |
| South Sudan                    | 0    | 0    | 3    | 3    | 0    | 0    | 0    | 0    |
| Spain                          | 4    | 4    | 4    | 4    | 3    | 4    | 3    | 4    |
| Sri Lanka                      | 3    | 3    | 4    | 4    | 3    | 3    | 3    | 3    |
| Sudan                          | 2    | 2    | 3    | 3    | 1    | 2    | 2    | 2    |
| Suriname                       | 3    | 3    | 4    | 4    | 1    | 1    | 2    | 2    |
| Svalbard and Jan Mayen Islands | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    |
| Sweden                         | 0    | 0    | 0    | 0    | 4    | 4    | 4    | 4    |
| Switzerland                    | 0    | 0    | 0    | 0    | 4    | 4    | 4    | 4    |
| Syrian Arab Republic           | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    |
| Tajikistan                     | 1    | 1    | 1    | 1    | 0    | 0    | 0    | 0    |
| Thailand                       | 3    | 3    | 3    | 4    | 2    | 2    | 2    | 2    |
| Timor-Leste                    | 3    | 3    | 3    | 3    | 0    | 0    | 3    | 3    |
| Togo                           | 0    | 0    | 0    | 3    | 0    | 0    | 0    | 3    |
| Tokelau                        | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    |
| Tonga                          | 0    | 3    | 3    | 3    | 2    | 2    | 2    | 2    |
| Trinidad and Tobago            | 3    | 3    | 3    | 3    | 3    | 3    | 3    | 3    |
| Tunisia                        | 3    | 3    | 4    | 3    | 3    | 3    | 4    | 4    |
| Turkey                         | 0    | 0    | 0    | 0    | 2    | 2    | 2    | 2    |
| Turkmenistan                   | 1    | 1    | 1    | 1    | 0    | 0    | 0    | 0    |
| Turks and Caicos Islands       | 0    | 0    | 0    | 1    | 0    | 0    | 0    | 0    |
| Tuvalu                         | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    |
| Uganda                         | 1    | 3    | 3    | 4    | 0    | 0    | 0    | 3    |
| Ukraine                        | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    |
| United Arab Emirates           | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    |
| United Kingdom                 | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    |
| United Republic of Tanzania    | 2    | 2    | 3    | 3    | 1    | 1    | 3    | 3    |
| United States of America       | 0    | 0    | 0    | 0    | 4    | 4    | 4    | 4    |
| United States Virgin Islands   | 0    | 0    | 0    | 0    | 1    | 1    | 2    | 2    |
| Uruguay                        | 3    | 3    | 3    | 4    | 0    | 0    | 0    | 0    |
| Uzbekistan                     | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    |
| Vanuatu                        | 1    | 1    | 1    | 1    | 0    | 0    | 0    | 1    |
| Venezuela (Bolivarian Republic of) | 3    | 3    | 4    | 3    | 0    | 0    | 0    | 0    |
| Viet Nam                       | 1    | 1    | 4    | 4    | 3    | 4    | 4    | 4    |
| Wallis and Futuna Islands      | 3    | 3    | 3    | 3    | 0    | 0    | 0    | 0    |
| Western Sahara                 | 2    | 2    | 2    | 2    | 2    | 2    | 2    | 2    |
| Yemen                          | 1    | 1    | 1    | 1    | 1    | 1    | 1    | 1    |
| Zambia                         | 1    | 1    | 3    | 3    | 1    | 1    | 3    | 3    |
| Zimbabwe                       | 2    | 2    | 2    | 3    | 1    | 2    | 2    | 2    |
### Appendix B. Regional analysis of data sources

#### Table B1.1. The number of non-annex 1 tropical countries by data source indicator value for ‘Use of RS’ and ‘Use of NFI’ in FRA 2005, 2010, 2015, and 2020 (n = 99).

| Data source indicator value | Use of RS for forest area monitoring | Use of NFI for forest monitoring |
|-----------------------------|-------------------------------------|----------------------------------|
|                             | 2005 | 2010 | 2015 | 2020 | 2005 | 2010 | 2015 | 2020 |
| Very good                   | 13   | 11   | 22   | 38   | 4    | 5    | 7    | 11   |
| Good                        | 22   | 30   | 30   | 31   | 17   | 21   | 29   | 46   |
| Intermediate                | 18   | 19   | 15   | 09   | 11   | 20   | 24   | 21   |
| Limited                     | 12   | 10   | 10   | 09   | 29   | 24   | 14   | 07   |
| Low                         | 34   | 29   | 22   | 14   | 38   | 29   | 25   | 14   |

#### Table B1.2. The number of African countries by data source indicator value for ‘Use of RS’ and ‘Use of NFI’ in FRA 2005, 2010, 2015, and 2020 (n = 58).

| Data source indicator value | Use of RS for forest area monitoring | Use of NFI for forest monitoring |
|-----------------------------|-------------------------------------|----------------------------------|
|                             | 2005 | 2010 | 2015 | 2020 | 2005 | 2010 | 2015 | 2020 |
| Very good                   | 0    | 0    | 03   | 08   | 00   | 00   | 02   | 02   |
| Good                        | 08   | 12   | 16   | 23   | 08   | 10   | 14   | 25   |
| Intermediate                | 13   | 13   | 12   | 08   | 05   | 12   | 13   | 12   |
| Limited                     | 10   | 07   | 06   | 05   | 19   | 14   | 09   | 03   |
| Low                         | 27   | 26   | 21   | 14   | 26   | 22   | 20   | 16   |

#### Table B1.3. The number of Asian countries by data source indicator value for ‘Use of RS’ and ‘Use of NFI’ in FRA 2005, 2010, 2015, and 2020 (n = 48).

| Data source indicator value | Use of RS for forest area monitoring | Use of NFI for forest monitoring |
|-----------------------------|-------------------------------------|----------------------------------|
|                             | 2005 | 2010 | 2015 | 2020 | 2005 | 2010 | 2015 | 2020 |
| Very good                   | 09   | 08   | 12   | 21   | 06   | 07   | 07   | 08   |
| Good                        | 09   | 13   | 11   | 06   | 09   | 10   | 11   | 15   |
| Intermediate                | 01   | 01   | 00   | 02   | 04   | 04   | 04   | 04   |
| Limited                     | 06   | 05   | 06   | 03   | 04   | 04   | 04   | 02   |
| Low                         | 23   | 21   | 19   | 16   | 25   | 23   | 22   | 19   |

#### Table B1.4. The number of European countries by data source indicator value for ‘Use of RS’ and ‘Use of NFI’ in FRA 2005, 2010, 2015, and 2020 (n = 50).

| Data source indicator value | Use of RS for forest area monitoring | Use of NFI for forest monitoring |
|-----------------------------|-------------------------------------|----------------------------------|
|                             | 2005 | 2010 | 2015 | 2020 | 2005 | 2010 | 2015 | 2020 |
| Very good                   | 02   | 04   | 05   | 04   | 10   | 13   | 18   | 23   |
| Good                        | 04   | 02   | 03   | 04   | 06   | 11   | 09   | 06   |
| Intermediate                | 01   | 01   | 01   | 01   | 02   | 01   | 01   | 01   |
| Limited                     | 01   | 01   | 01   | 01   | 01   | 02   | 01   | 01   |
| Low                         | 44   | 42   | 40   | 40   | 31   | 23   | 21   | 19   |
Table B1.5. The number of countries in North and Central America by data source indicator value for ‘Use of RS’ and ‘Use of NFI’ in FRA 2005, 2010, 2015, and 2020 (n = 41).

| Data source indicator value | Use of RS for forest area monitoring | Use of NFI for forest monitoring |
|-----------------------------|-------------------------------------|---------------------------------|
|                             | 2005  | 2010 | 2015 | 2020 | 2005 | 2010 | 2015 | 2020 |
| Very good                   | 05    | 04   | 04   | 06   | 03   | 03   | 03   | 04   |
| Good                        | 04    | 07   | 07   | 08   | 03   | 05   | 06   | 08   |
| Intermediate                | 03    | 04   | 05   | 07   | 03   | 03   | 05   | 05   |
| Limited                     | 04    | 08   | 07   | 10   | 08   | 08   | 05   | 04   |
| Low                         | 25    | 18   | 18   | 10   | 24   | 22   | 22   | 20   |

Table B1.6. The number of countries in Oceania by data source indicator value for ‘Use of RS’ and ‘Use of NFI’ in FRA 2005, 2010, 2015, and 2020 (n = 25).

| Data source indicator value | Use of RS for forest area monitoring | Use of NFI for forest monitoring |
|-----------------------------|-------------------------------------|---------------------------------|
|                             | 2005  | 2010 | 2015 | 2020 | 2005 | 2010 | 2015 | 2020 |
| Very good                   | 02    | 02   | 02   | 03   | 01   | 01   | 01   | 01   |
| Good                        | 02    | 04   | 05   | 04   | 00   | 02   | 02   | 03   |
| Intermediate                | 05    | 05   | 04   | 05   | 04   | 06   | 06   | 08   |
| Limited                     | 01    | 03   | 03   | 03   | 06   | 05   | 05   | 04   |
| Low                         | 15    | 11   | 11   | 10   | 14   | 11   | 11   | 09   |

Table B1.7. The number of countries in South America by data source indicator value for ‘Use of RS’ and ‘Use of NFI’ in FRA 2005, 2010, 2015, and 2020 (n = 14).

| Data source indicator value | Use of RS for forest area monitoring | Use of NFI for forest monitoring |
|-----------------------------|-------------------------------------|---------------------------------|
|                             | 2005  | 2010 | 2015 | 2020 | 2005 | 2010 | 2015 | 2020 |
| Very good                   | 05    | 04   | 10   | 11   | 00   | 00   | 01   | 03   |
| Good                        | 05    | 06   | 02   | 01   | 02   | 02   | 03   | 04   |
| Intermediate                | 02    | 02   | 01   | 01   | 03   | 03   | 05   | 04   |
| Limited                     | 00    | 00   | 00   | 00   | 01   | 03   | 00   | 00   |
| Low                         | 02    | 02   | 01   | 01   | 08   | 06   | 05   | 03   |

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References
Angelsen A, Jagger P, Babigumira R, Belcher B, Hogarth N J, Bauch S, Börner J, Smith-Hall C and Wunder S 2014 Environmental income and rural livelihoods: a global-comparative analysis World Dev. 64 S12–S28
Clarke N et al 2011 Availability, accessibility, quality and comparability of monitoring data for European forests for use in air pollution and climate change science iForest Biogeosc. For. 4 162–6
Daniel T C et al 2012 Contributions of cultural services to the ecosystem services agenda Proc. Natl Acad. Sci. 109 8812–9
Duchelle A E, Seymour F, Brockhaus M, Angelsen A, Larson A M, Moeliono M, Wong G Y, Pham T T and Martius C 2019 Forest-based climate mitigation; lessons from REDD+ implementation (available at: www.wri.org/publication/forest-based-climate-mitigation)
Friedlingstein P et al 2019 Global carbon budget 2019 Earth Syst. Sci. Data 11 1783–838
GFOC-GOLD 2016 A sourcebook of methods and procedures for monitoring and reporting anthropogenic greenhouse gas emissions (available at: www.gfo.org/)
emissions and removals associated with deforestation, gains and losses of carbon stocks in forests remaining forests, and forestation GOFC-GOLD Report version (available at: www.gfoi.org/methods-guidance-documentation)

Gore M L, Ratsimbazafy J and Lute M L 2013 Rethinking corruption in conservation crime: insights from Madagascar Conserv. Lett. 6 430–8

Grissino B W et al 2017 Natural climate solutions Proc. Natl Acad. Sci. USA 114 11645–50

Grissino B W et al 2020 National mitigation potential from natural climate solutions in the tropics Phil. Trans. R. Soc. B 375 1794

Hansen M C et al 2013 High-resolution global maps of 21st-century forest cover change Science 342 850–3

Hansen M C, Stehman S V, Potapov P V, Arunawati B, Stolle F and Pittman K 2009 Quantifying changes in the rates of forest clearing in Indonesia from 1990 to 2005 using remotely sensed data sets Environ. Res. Lett. 4 034001

Herold M and Skutsch M 2011 Monitoring, reporting and verification for national REDD+ programmes: two proposals Environ. Res. Lett. 6 014002

Houghton R A, House J I, Pongratz J, van der Werf G R, Defries R S, Hansen M C, Le Quéré C and Ramankutty N 2012 Carbon emissions from land use and land-cover change Biogeosciences 9 5125–42

IPCC 2000 2006 IPCC guidelines for national greenhouse gas inventories: volume 4—agriculture, forestry and other land use (Geneva: IPCC)

Joseph S, Herold M, Sunderlin W D and Verchot L V 2013 REDD+ readiness: early insights on monitoring, reporting and verification systems of project developers Environ. Res. Lett. 8 034038

Kauffman D and Kraay A 2019 Worldwide governance indicators (available at: https://info.worldbank.org/governance/wgi/) (Accessed 25 May 2020)

Keenan R J, Reams G A, Achard F, de Freitas J V, Grainger A and Lindquist E 2015 Dynamics of global forest area: results from the FAO Global Forest Resources Assessment 2015 For. Ecol. Manage. 352 9–20

Kim D, Kim D, Lee D-H, Park S and Kim S 2019 Centralization of the global REDD+ financial network and implications under the new climate regime Forests 10 753

Lorenz M and Fischer R 2013 Pan-European forest monitoring: an overview Developments in Environmental Science vol 12 (Amsterdam: Elsevier) pp 19–32

Martinez Pastur G, Perera A H, Peterson U and Iverson L R 2018 Ecosystem services from forest landscapes: an overview In Ecosystem Services from Forest Landscapes (Berlin: Springer) pp 1–10

McAlpine J L and Church B 2018 Finding finance for forests: an overview survey of known sources, 2018: a contribution to the FAO Global Forest Resources Assessment 2015 (Amsterdam: Elsevier) pp 49–73

Tomppo E, Gschwantner T, Lawrence M and McRoberts R E 2010 National Forest Inventories: Pathways for Common Reporting (Berlin: Springer) (https://doi.org/10.1007/978-90-481-3253-1)

UN-REDD 2013 National forest monitoring systems: monitoring and measurement, reporting and verification (M & MRV) in the context of REDD+ activities (available at: www.fao.org/)

Van Bodegom J, Wigboldus S, Blundell A G, Harwell E E, Savenije H, Rametsteiner E and Officer S 2012 An approach for integrating forest governance into national forest-related monitoring systems van der Werf G R, Morton D C, Defries R S, Olivier J G J, Kasibhatla P S, Jackson R B, Collatz G J and Randerson J T 2009 CO2 emissions from forest loss Nat. Geosci. 2 737

Vedeld P, Angrøen J, Boji J, Sjaastad E and Kobugabe Berg G 2007 Forest environmental incomes and the rural poor For. Policy Econ. 9 869–79

Vidal C, Alberdi I, Redmond J, Vestman L, Lanz A and Schadauer K 2016 The role of European National Forest Inventories for international forestry reporting Ann. For. Sci. 73 793–806

Wittke S, Yu X, Karjalainen M, Hyppä J and Puttonen E 2019 Comparison of two-dimensional multitemporal Sentinel-2 data with three-dimensional remote sensing data sources for forest inventory parameter estimation over a boreal forest Int. J. Appl. Earth Obs. Geoinf. 76 167–78