Food and Agriculture Organization of the United Nations

Technological innovation driving transparent forest monitoring and reporting for climate action

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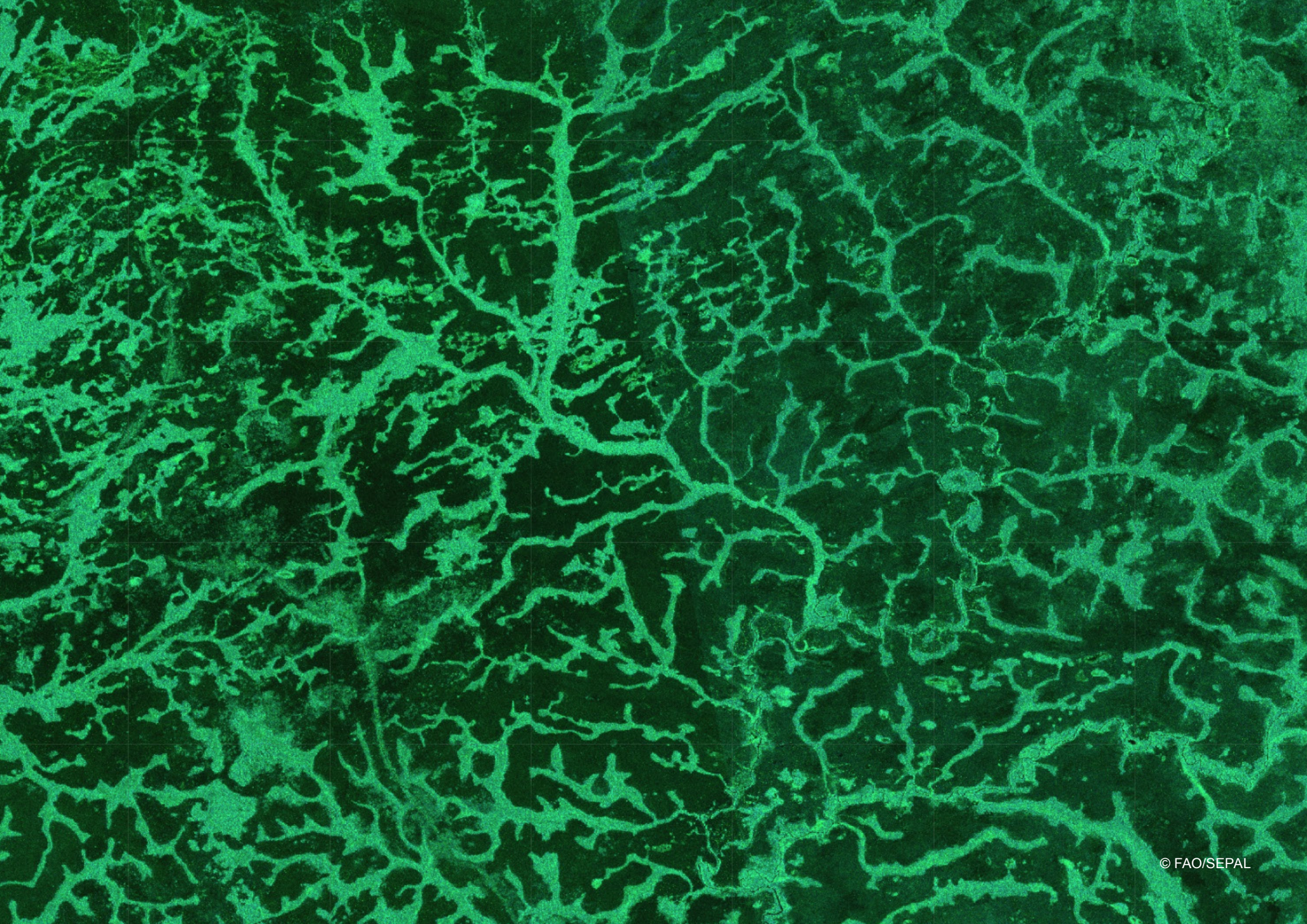
Abbreviations

ART	Architecture for REDD+ Transactions
BTR	biennial transparency report
BUR	biennial update report
ER	emission reduction
FAO	Food and Agriculture Organization of the United Nations
FCPF-CF	Forest Carbon Partnership Facility's Carbon Fund
GCF	Green Climate Fund
GFC	Global Forest Change
GFOI	Global Forest Observations Initiative
MRV	measurement, reporting and verification
NDC	nationally determined contribution
NFI	national forest inventory
QA/QC	quality assurance/quality control
REDD+	Reducing Emissions from Deforestation and Forest Degradation, and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks in developing countries
SEPAL	System for Earth Observation, Data Access, Processing and Analysis for Land Monitoring
TREES	The REDD+ Environmental Excellence Standard
UNFCCC	United Nations Framework Convention on Climate Change

Units and formulae

ha	hectare(s)
m	metre(s)
tCO_2e	tonne(s) of carbon dioxide equivalent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Summary

Forests play an important role in climate action. Transparent and reliable assessments of forest carbon fluxes are needed to understand their contribution in climate change mitigation and unlock results-based finance. To date, results-based finance for forest-related emission reductions (ERs) has been limited; however, it has seen considerable growth in recent years.

Technological innovation in forest monitoring can help to increase the reliability of data on forestbased mitigation contributions, thus unlocking carbon finance from a variety of sources, including the private sector. The past decade has seen important technological innovations in forest monitoring with improvements in available imagery, global products and improved algorithms, area estimation methodologies, and platforms to access and analyse spatial data.

This paper reviews how countries are benefiting from these technological innovations to accurately monitor forest dynamics and improve reporting of anthropogenic, forest-related emissions and removals to the United Nations Framework Convention on Climate Change (UNFCCC).

As of February 2024, important milestones include:

- Since 2014, 63 countries have submitted a reference level to the UNFCCC; 22 countries have reported forest-related ERs of 14.0 billion tonnes of carbon dioxide equivalent (tCO_2 e) achieved between 2006 and 2022 to the UNFCCC.
- There has been enormous technological progress over the years, enabling increasingly robust estimation. Recent submissions reveal an increased use of satellite imagery with higher spatial and temporal resolution, such as Planet and Sentinel. Open-source solutions are widely used by countries, with 89 percent using Open Foris, a set of free software platforms that help countries measure, monitor and report on forestry progress, take sciencebased actions, and accelerate forest pathways. Uncertainty reporting has nearly doubled over the past ten years.
- To date, results-based finance for forest-related ERs has been limited, but more robust estimation methods increasingly enable accessing new types of climate finance, including through linkage to carbon markets. Since 2020, 16 countries have reported ERs to the Forest Carbon Partnership Facility's Carbon Fund (FCPF-CF) and/or The REDD+ Environmental Excellence Standard of the Architecture for REDD+ Transactions (ART-TREES).
- Technological solutions and capacity development for ER reporting can act as an engine enabling better resource management and improved access to climate finance.

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Introduction: The role of technological innovation in forest monitoring

Many countries include forests in their nationally determined contributions (NDCs) to meet the goals of the Paris Agreement (Crumpler *et al.*, forthcoming), but a significant share of country targets is conditional on international climate finance (Haupt *et al.*, 2021). Robust assessments of forest area changes and carbon fluxes are crucial for a better understanding of and support for forests' contribution to climate change mitigation. Reliable and transparent data on forest-related emission reductions (ERs)[1] can attract climate finance. Forest monitoring has seen a technological revolution over the past decade, with an increased availability of higher resolution imagery (Roy *et al.*, 2021; Malenovský *et al.*, 2012), an increased availability of spatially explicit global products with tree cover loss classifications (Hansen *et al.*, 2013; Vancutsem *et al.*, 2021), and more advanced algorithms using dense time series to filter out seasonality and other noise.[2] These advances, together with the capacity development that has taken place in many countries, have helped countries to improve their forest area (change) estimates and forest-related emission and removals estimates over time (Nesha *et al.*, 2021).

The science around the deduction of statistics using remote sensing-based forest area estimation has also greatly advanced, providing recommendations for robust area estimations (Olofsson *et al.*, 2013, 2014; Stehman, 2014; GFOI, 2020; Jonckheere *et al.*, 2024). One important recommendation is the use of sample-based estimates rather than pixel counts (map area statistics) (Olofsson *et al.*, 2014; GFOI, 2020; Venter *et al.*, 2024). Pixel counting is the reporting of area statistics directly from maps (regardless of classification errors). In theory, if maps were perfect, pixel counts could be used for reporting on land cover and land cover change areas. However, most maps carry errors and biases at all scales, especially for smaller area change classes. Without additional details on map accuracy for the specific class of interest, pixel counts are therefore not reliable.[3] Sample unit observations through visual interpretations of remotely sensed data such as aerial imagery or satellite imagery are typically considered of higher quality than map data; they can be used not only to provide information on map accuracy, but also to correct map area estimates for classification errors and calculate the associated confidence interval around the estimate (these are referred to as sample-based area estimates) (Olofsson *et al.*, 2014; Venter *et al.*, 2024; Jonckheere *et al.*, 2024). In this paper, we discuss progress on United Nations Framework Convention on Climate Change (UNFCCC) reference level and emission reduction reporting, as well as the role of technological innovation to enhance accuracy and transparency of reporting over time.

1 Emission reductions in this publication refers to both emission reductions and removal increases.

2 Examples include: BFAST (Verbesselt *et al.*, 2013), CUSUM (Kellndorfer, 2019), CCDC (Zhu and Woodstock, 2014) and LandTrendR (Kennedy *et al.*, 2010) – referring to Breaks For Additive Season and Trend, Cumulative Sum, Continuous Change Detection and Classification, and Landsat-based detection of trends in disturbance and recovery, respectively.

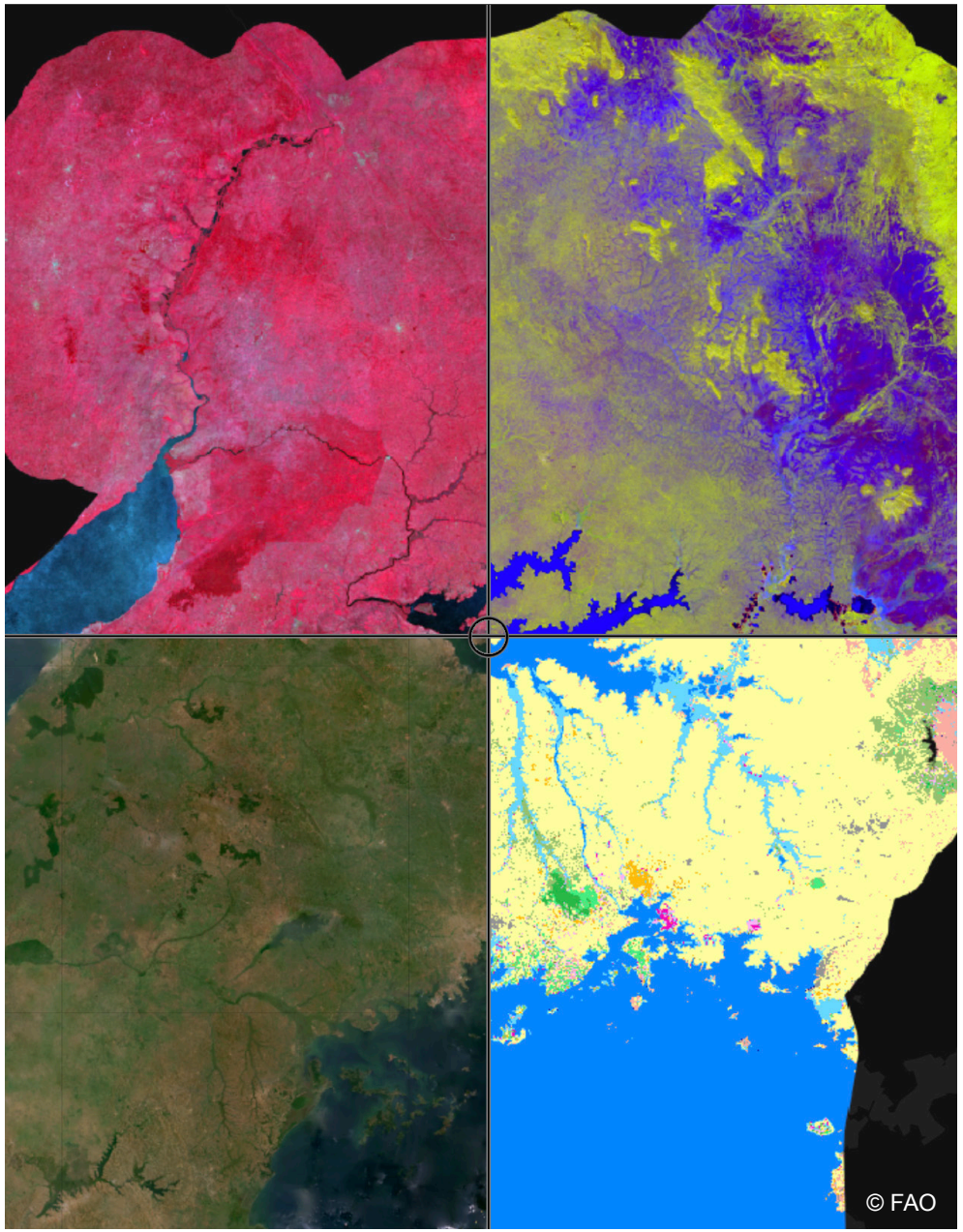
3 Sandker *et al.* (2021) analysed a few countries where pixel counts were replaced with sample-based area estimates, resulting in a downwards revision of deforestation estimates in two cases by a factor of 3 and 15, respectively.

Forest-based emission reductions reported to the UNFCCC and beyond

Article 5 of the Paris Agreement calls for action on Reducing Emissions from Deforestation and Forest Degradation, and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks in developing countries (REDD+), a vehicle for developing countries to contribute to forest-based climate action. In 2013, the Warsaw Framework (the Nineteenth Conference of the Parties to the UNFCCC) finalized decisions related to the measurement, reporting and verification (MRV) of emissions and removals from REDD+ activities, marking the beginning of the voluntary submission of reference levels by countries[4].

By February 2024, **63 countries** had submitted a reference level through **93 reference level submissions** (Figure 1), of which 90 percent were for the national scale. Subsequently, **22 countries submitted ERs** against the technically assessed reference levels through 32 biennial update report (BUR) technical annexes.

The ERs reported to the UNFCCC total **14.0 billion tonnes of carbon dioxide equivalent (tCO_2 e)** achieved between 2006 and 2022, where the **large majority of ERs are from reduced deforestation (96 percent)**. The reference levels cover a **forest area of 1.6 billion ha**, which is **72 percent of the forest area in developing countries** (FAO, 2020). The countries submitting a reference level together add to approximately **80 percent of global deforestation** (FAO, 2020).[5]



4 A reference level is a benchmark for assessing a country's performance in implementing REDD+.

5 For deforestation over the 2015–2020 period. These are deforestation areas reported to the Global Forest Resources Assessment 2020, gap-filled with negative forest area change for countries that did not report deforestation.

Figure 1. Overview of reference level and emission reduction submissions to the UNFCCC

Only one in three countries with a reference level have submitted ERs to the UNFCCC. Factors that explain a lack of ER reporting include: the **lack of climate finance to pay for UNFCCC reported results**,[6] the **large effort MRV requires**, and the fact that the vehicle for ER reporting is the BUR/biennial transparency report (BTR), which sometimes includes **a different timeline**. In some cases, there **may not have been a reduction in emissions**.

6 The GCF, the financial mechanism of the UNFCCC, launched a REDD+ results-based payment pilot programme in 2017 with USD 500 million, but was depleted in 2020 by eight countries: Argentina, Brazil, Chile, Colombia, Costa Rica, Ecuador, Indonesia and Paraguay.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While no ERs were reported to the UNFCCC in 2023, **many countries reported ERs in recent years to the Forest Carbon Partnership Facility's Carbon Fund (FCPF-CF) and The REDD+ Environmental Excellence Standard of the Architecture for REDD+ Transactions (ART-TREES)** (Figure 2).[7] Out of the 15 countries reporting ERs to the FCPF, only 7 (47 percent) also reported ERs to the UNFCCC; of those 7, most reported ERs to the UNFCCC for earlier years (that is, before 2018) without overlap with the ERs reported to the FCPF for more recent years (that is, after 2018). Of the three countries reporting ERs to ART, two (Costa Rica and Guyana) also reported ERs to the UNFCCC: Costa Rica for earlier years without overlap, Guyana for earlier and recent years with a full overlap of years for which ERs are also reported to ART-TREES.

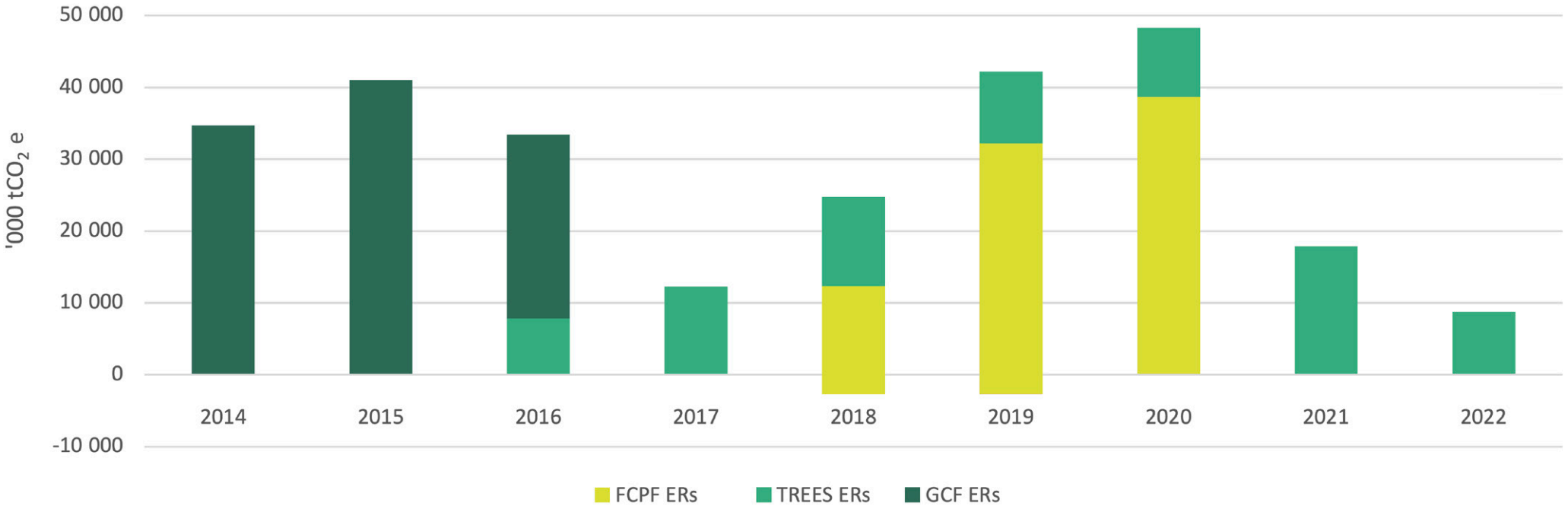
Figure 2. Emission reduction report submissions to the UNFCCC, ART-TREES and FCPF-CF

Note: UNFCCC ERs are reported in a technical annex to the BUR/BTR, while FCPF-CF ERs and ART-TREES ERs are reported in a monitoring report. Many ERs submitted to the FCPF-CF and ART-TREES are still undergoing validation/verification and may change as a result of this process. These are the ERs as assessed by the countries without considering ERs allocated in buffers. ART-TREES numbers have been corrected for double-counting as some reporting years overlap with ERs reported to the FCPF-CF.

7 The FCPF manages The Carbon Fund, a jurisdictional REDD+ results-based payment pilot programme, ART manages TREES, a jurisdictional REDD+ carbon accounting standard. The differences between them are explained in Sandker *et al.* (2022)

To be eligible for ER payments under the FCPF and ART, countries need to meet carbon accounting requirements that **build upon UNFCCC modalities and go beyond**. This means that countries with ERs under the UNFCCC will not necessarily have ERs that comply with the FCPF or ART, or are eligible for Green Climate Fund (GCF) results-based payments. Figure 3 shows the amount of "creditable ERs for payments": ERs that were awarded results-based payments by the GCF or that have been submitted to the FCPF or ART. To access climate finance, countries will need to comply with specific carbon accounting requirements. Notably, they will have to apply a specific reference period (for example, five years for ART) and need to use advanced area estimation methodologies such as sample-based area estimation. Countries will need to apply the best science and technology for robust emission (reduction) estimates. Cost-effective technological innovation can help countries gain access to much needed climate finance and improve the quality of reporting. More details on reported reference levels and emission reductions can be found in this dashboard.

Figure 3. Emission reductions for payments



Note: Emission reductions that were awarded results-based payments by the GCF or that have been submitted to the FCPF or ART, minus the amount estimated by the respective deduction mechanism established by the FCPF, ART-TREES or GCF: total ERs for payments are 101 million tCO_2 e for GCF, 94 million tCO_2 e for the FCPF (or 88 considering the negative ERs reported by Chile in the 2018–2019 period), and 60 million tCO_2 e for ART-TREES. The average deductions were 22 percent for GCF (scorecard deduction), 23 percent for the FCPF and 11 percent for ART-TREES (deductions based on uncertainty and other criteria, which differ per standard); GCF ERs are non-market results-based payments while TREES ERs are market-oriented climate finance that might be used for offsetting.

The increased use of technological innovation in country reporting

Improvements can be seen in available imagery, global products and improved algorithms, area estimation methodologies, and platforms and solutions to access and analyse spatial data.

Imagery

All UNFCCC reference level submissions make use of Landsat imagery, underscoring the importance of this satellite imagery and its long-term consistent archive for forest monitoring, especially when assessing historical periods. Landsat imagery has undergone many improvements over its lifespan, including upgraded sensors, increased acquisitions over time and more advanced pre-processing routines, which enable improved forest change assessments. Sentinel-1 (radar) imagery became available in 2014, while Sentinel-2 (optical) was launched in 2016. Planet imagery is available from 2014/15 onwards. Both have a higher spatial resolution (3–5 m for Planet and 10–20 m for Sentinel versus 30 m for Landsat) and a higher temporal resolution than Landsat (16-day revisit for Landsat versus approximately 5-day revisit for Sentinel-2 versus approximately 1-day revisit for Planet), the latter being especially helpful for assessing areas with frequent cloud cover. Where reference level submissions before 2016 were relying solely on Landsat imagery (Figure 4), **100 percent of the submissions after 2022 mention the use of Sentinel and 50 percent the use of Planet imagery**, allowing for more accurate change assessments.

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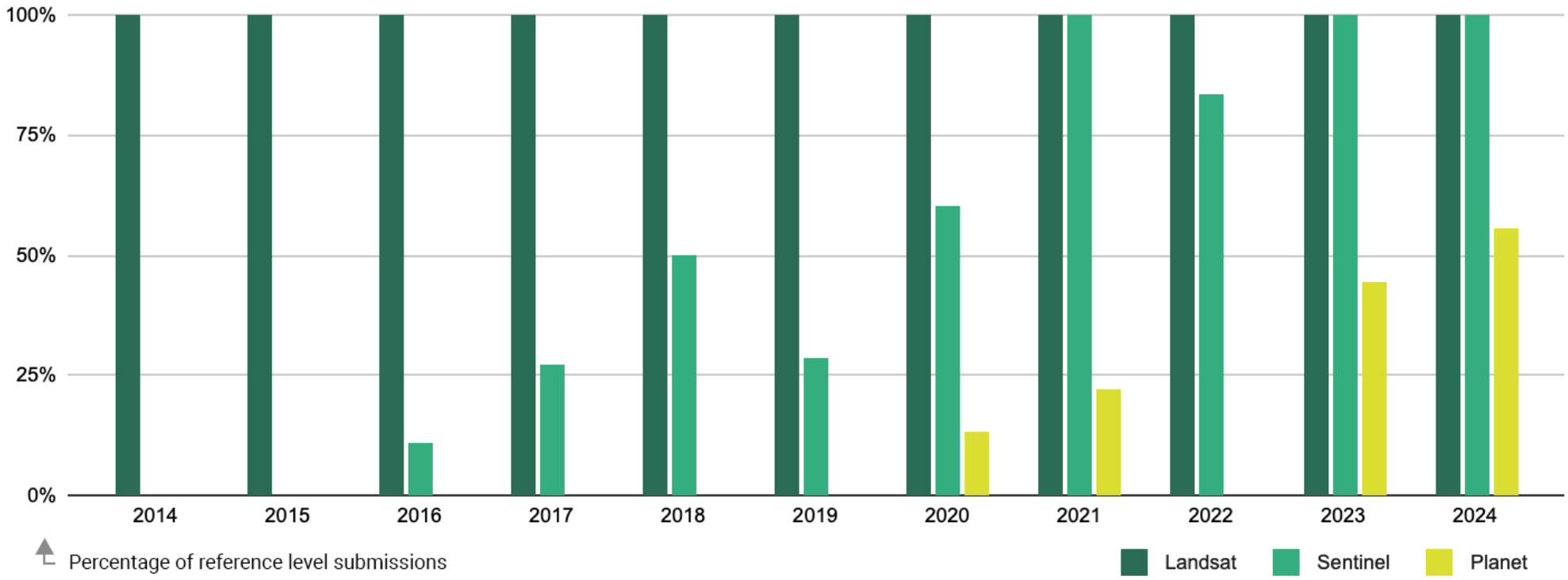
Figure 4. Landsat, Sentinel and Planet imagery used in UNFCCC reference level submissions



Global tree cover loss products

Though global products are never used "off-shelf" by countries for their forest assessments (Melo *et al.*, 2023), multiple countries have made use of global products as an interim step in their forest area change assessments to: collect deforestation training data, gap-fill missing land uses, "translate" tree cover loss into a deforestation classification (combining it with national forest maps), and use it as stratification for sample-based area estimates (Sandker *et al.*, 2021). Furthermore, they are frequently used for quality assurance/quality control (QA/QC). In particular, the Global Forest Change (GFC) product (Hansen *et al.*, 2013) has been used for these purposes (Table 1); more recently, the Tropical Moist Forest product (Vancutsem *et al.*, 2021) has also been used. In 2024, Bolivia (Plurinational State of), Congo and Côte d'Ivoire used agreements among multiple global products, sometimes in combination with machine learning techniques and dense time series algorithms, to improve their national forest area (change) statistics.

Table 1. Uses of the Global Forest Change product in UNFCCC reference level reporting

	Countries			Total	Share of countries*
	Africa	**Asia and the Pacific**	**Latin America and the Caribbean**		
Using GFC data as interim step in forest (change) assessment	• Congo • Côte d'Ivoire • Equatorial Guinea • Ethiopia • Liberia • Madagascar • Nigeria • Zambia • Zimbabwe	• Bhutan • Cambodia • Myanmar • Sri Lanka	• Bolivia (Plurinational State of) • Costa Rica	**15**	**24%**
Using GFC data for QA/QC only**	• Democratic Republic of the Congo • Ghana • Malawi • Togo • Uganda • United Republic of Tanzania	• Indonesia • Lao People's Democratic Republic • Mongolia • Nepal • Papua New Guinea • Solomon Islands • Timor-Leste	• Chile • Colombia • Ecuador • Honduras • Paraguay • Peru • Suriname	**20**	**32%**
				35	**56%**

Notes: * 63 total.
** Either by the country or the technical assessment.

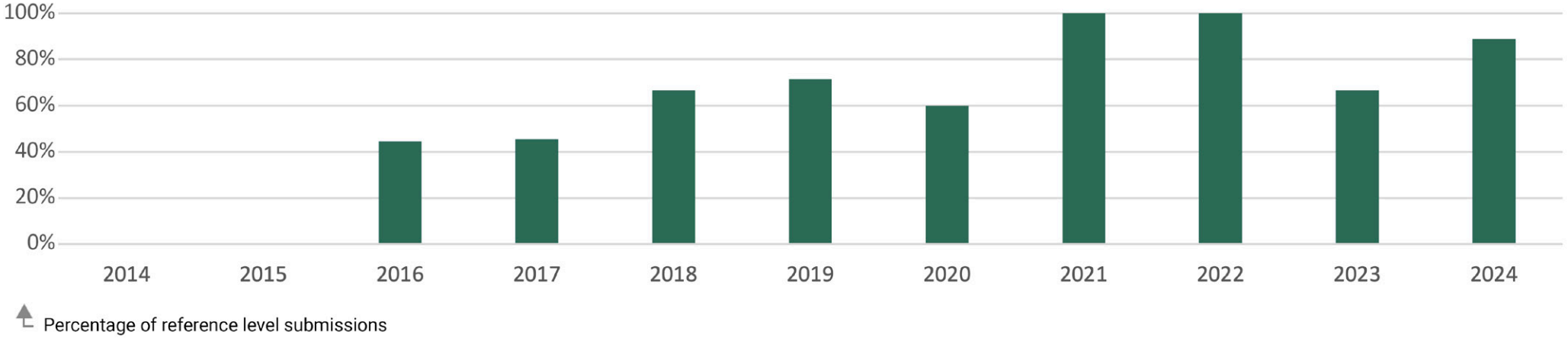
National forest inventories and biomass maps

Of the 63 reporting countries, **53 (84 percent) have a national forest inventory** (NFI) or are in the process of collecting their NFI data. Though sometimes complemented with Intergovernmental Panel on Climate Change (IPCC) default values, NFI data is the most frequent data source for emission factors. The 10 countries (16 percent) that do not have an NFI all use inventory data from local inventories or from neighbouring countries. Global biomass maps (Saatchi *et al.*, 2011; Baccini *et al.*, 2012; Avitabile *et al.*, 2016) are not used by countries for their emission factors but are used for QA/QC, especially in the technical assessment process. In recent years, a few countries have made use of nationally produced biomass maps, such as Bolivia (Plurinational State of) and Brazil. Biomass maps may suffer from similar accuracy issues as forest change maps and are therefore not necessarily a more accurate data source than NFI data (for example, Zambia created a biomass map but is using it for stratification only, whereas the emission factors are calculated from the NFI).

Area estimation methodologies

Sample-based area estimation is considered good practice in the scientific community to account for classification errors and quantify random errors through the calculation of confidence intervals. Carbon accounting standards, like ART-TREES, include sample-based area estimates for ER submissions as good practice to be eligible for payments. Figure 5 shows the methodological improvement countries made over time: up to 2019, only 50 percent of countries used sample-based area estimates, while **over the most recent five years this percentage rose to 79 percent**.

Figure 5. Average share of UNFCCC reference level submissions using sample-based area estimates to assess deforestation



Open-source solutions

Countries' capacities to access and analyse satellite imagery to create land cover change maps and collect sample data greatly improved with newly developed open-source solutions (Bey *et al.*, 2016; SEPAL, 2022; Tzamtzis *et al.*, 2019). An important platform is Google Earth Engine, used by at least **46 countries (73 percent)**.[8] Other frequently used open-source solutions are from Open Foris, a set of free and open-source software and platforms developed by the Food and Agriculture Organization of the United Nations (FAO) for accessing and analysing data. Table 2 provides an overview of Open Foris solutions that facilitate flexible and efficient data collection, analysis and reporting. While 73 percent of all 2014–2019 reference level submissions used at least one Open Foris solution, this share increased to 92 percent for the 2020–2024 submissions. In total, **89 percent** of the submitting countries use at least one of the solutions (Table 2).

8 Many Open Foris tools make use of Google Earth Engine for all or part of their functionality, thus the actual percentage of countries using Google Earth Engine may be higher.

Table 2. Countries using Open Foris solutions for emission/removal estimates in their UNFCCC reference levels

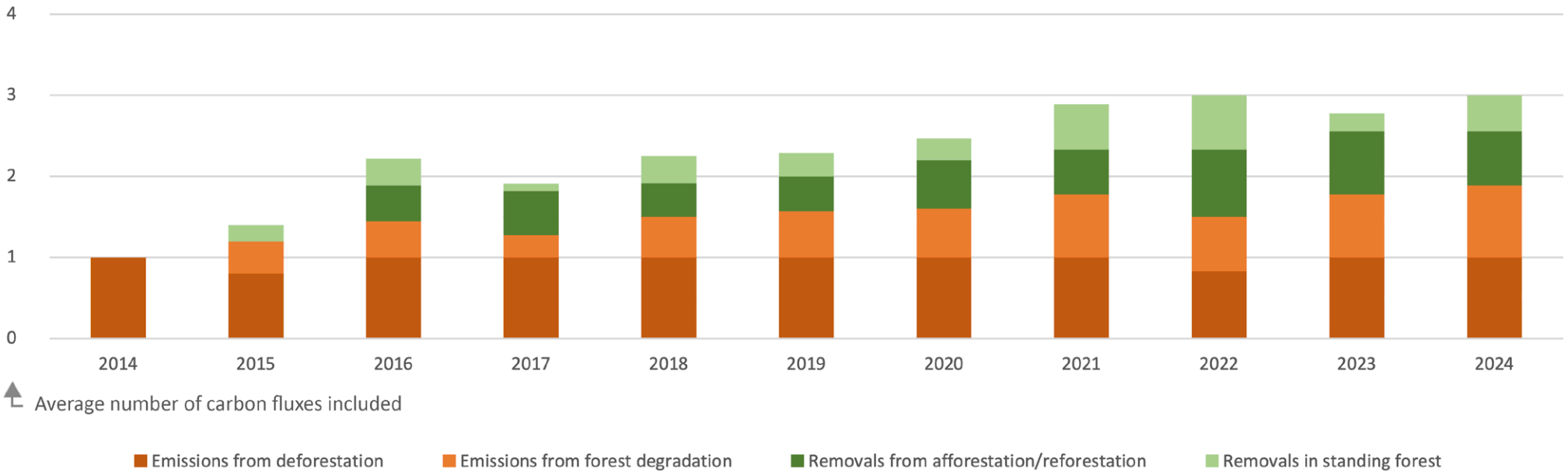
	Collect/Collect Mobile/Calc	Collect Earth	SEPAL	Any Open Foris tool
Description	*Survey design, data collection, data management, processing of ground data (mostly for NFI)*	*Augmented visual interpretation tool for land monitoring (remote sensing)*	*System for Earth Observation, Data Access, Processing and Analysis for Land Monitoring (geospatial analysis)*	
Africa	Côte d'Ivoire, Democratic Republic of the Congo, Ethiopia, Kenya, Liberia, Nigeria, Sudan, Uganda, United Republic of Tanzania, Zambia	Burkina Faso, Congo, Côte d'Ivoire, Democratic Republic of the Congo, Equatorial Guinea, Eswatini, Ethiopia, Gabon, Ghana, Guinea-Bissau, Kenya, Liberia, Madagascar, Mozambique, Nigeria, Sudan, Togo, Uganda, Zambia, Zimbabwe	Congo, Côte d'Ivoire, Democratic Republic of the Congo, Equatorial Guinea, Ethiopia, Ghana, Liberia, Nigeria, Sudan, Uganda, Zambia, Zimbabwe	21
Asia and the Pacific	Bangladesh, Bhutan, Cambodia, Myanmar, Nepal, Papua New Guinea, Solomon Islands, Sri Lanka, Thailand, Timor-Leste, Vanuatu, Viet Nam	Bangladesh, Bhutan, Cambodia, Lao People's Democratic Republic, Mongolia, Myanmar, Nepal, Pakistan, Papua New Guinea, Philippines, Samoa, Solomon Islands, Sri Lanka, Thailand, Timor-Leste, Vanuatu, Viet Nam	Bangladesh, Bhutan, Cambodia, Lao People's Democratic Republic, Myanmar, Papua New Guinea, Samoa, Sri Lanka, Thailand	17
Latin America and the Caribbean	Argentina, Ecuador, Honduras, Mexico, Nicaragua, Panama, Paraguay, Saint Lucia	Belize, Bolivia (Plurinational State of), Chile, Dominica, Dominican Republic, Ecuador, El Salvador, Guatemala, Honduras, Mexico, Nicaragua, Panama, Peru, Saint Lucia, Suriname	Chile, Dominican Republic, Ecuador, Honduras, Peru, Suriname	18
Total countries	**31**	**51**	**27**	**56**
Share of countries using Open Foris tool(s)*	**49%**	**81%**	**43%**	**89%**

Notes: * 63 total.

How countries enhanced the transparency of their estimates through technological innovation

The reporting of overall uncertainties has increased over time from 37 percent of the 2014–2018 submissions reporting overall uncertainty of the reference level value, to 65 percent of the 2019–2023 submissions reporting overall uncertainty. In 2024, this number dropped to 11 percent but several countries have indicated that they were adding this during the technical assessment, so this percentage may increase. The scope of reporting also increased over time (Figure 6): where in 2014 only deforestation was included, in 2024, 89 percent of the submissions also included emissions from forest degradation. Removals from standing forest are the least covered flux. This flux is challenging to measure with accuracy and may include significant non-anthropogenic removals (Donegan and Sandker, 2022; Grassi *et al.*, 2022).

Figure 6. Average share of carbon fluxes covered in the UNFCCC reference level submissions



Note: Emissions from deforestation (forest to non-forest), emissions from forest degradation (forest remaining forest), removals from afforestation/reforestation (non-forest to forest) and removals in standing forest (forest remaining forest).

Nesha *et al.* (2021) also find that country capacities to measure, report and verify forest-related emissions and removals have greatly increased over the past 10 to 15 years with **roughly a doubling of countries with good to very good remote sensing and NFI capacities** between 2005 and 2020.

Total climate finance contributions to the agriculture and land-use sector between 2000 and 2020 amounted to USD 162 billion (Galbiati and Bernoux, 2022). To date, only **about USD 3 billion results-based finance has been disbursed or committed** through ER purchase agreements to 22 countries over 15 years (authors' estimation), more than half of which through bilateral agreements. An additional USD 1.5 billion was pledged through the Lowering Emissions by Accelerating Forest finance (LEAF) coalition, a public–private partnership for forest finance that is accessible when MRV requirements of the ART-TREES standard are met. Despite the limited results-based finance to date, nature-based climate finance has seen considerable growth over the past years (Forest Trends' Ecosystem Marketplace, 2023). Carbon Direct (2023) stresses the importance of the quality of carbon credits for future nature-based finance opportunities; **quality carbon credit purchases have grown by a factor of five approximately from 2021 to 2023**.

Conclusion: Forest monitoring for enhanced transparency and climate finance

Over the past 10 to 15 years, countries have made tremendous progress on forest-based emissions and removals reporting, and have managed to take advantage of technological innovations for producing more accurate assessments at lower costs. Reference level reporting saw an **increased use of imagery of higher spatial and temporal resolution, improved area estimation methodologies, increased use of open-source solutions and platforms, and an almost doubling in uncertainty reporting over the past 10 years**. This progress is much needed to provide countries access to results-based climate finance and realize their conditional NDC targets. **Technological innovations can form steppingstones for countries to gain access to this much needed finance**, as well as help them reinvest in forestry and the implementation of their NDCs.

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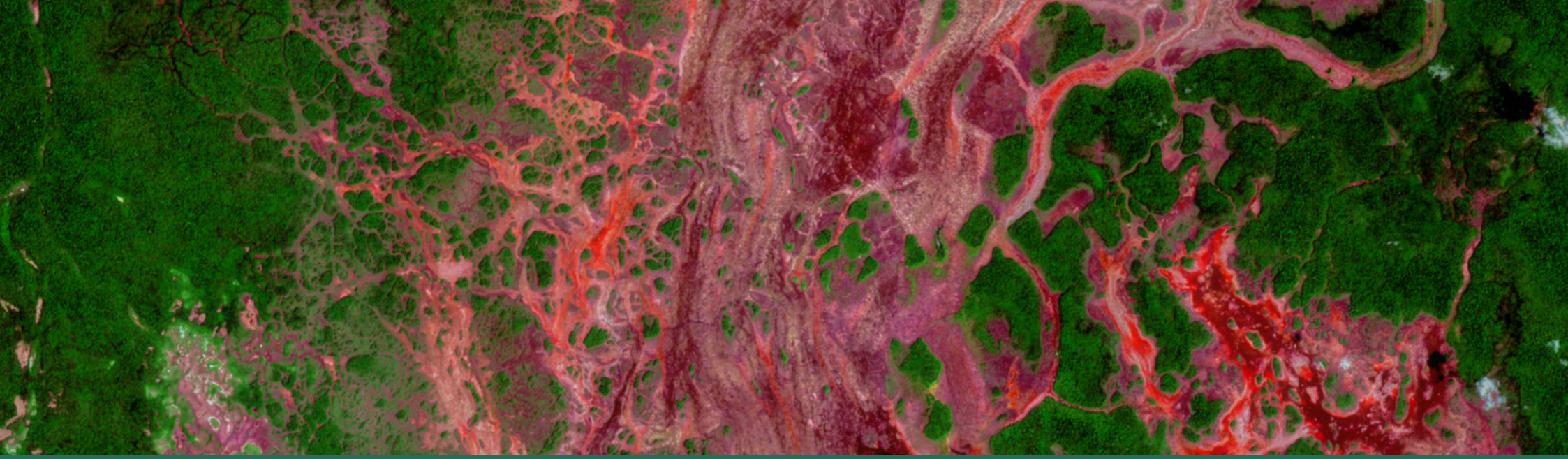

This paper reviews how countries are benefiting from technical innovations in their monitoring and reporting of forest-related emissions and removals to the United Nations Framework Convention on Climate Change (UNFCCC).

Forests play an important role in climate action. They are often mentioned in nationally determined contributions (NDCs) with targets conditional on international climate finance. Despite countries reporting forest-related emission reductions (ERs) of 14.0 billion tonnes of carbon dioxide equivalent (tCO_2 e) to the UNFCCC, results-based finance for ERs has been limited. Nonetheless, more robust estimation methods have increasingly enabled accessing new sources of climate finance, including from the private sector. As such, technological solutions and capacity development for ER reporting can act as an engine that enables better resource management and improved access to climate finance.

There has been enormous technological progress over the last decade, allowing increasingly robust forest dynamic assessments. Recent UNFCCC reference level submissions reveal an increased use of satellite imagery with higher spatial and temporal resolution: initial submissions relied entirely on Landsat imagery; after 2022, 100 percent used Sentinel and 50 percent used Planet imagery. Open-source solutions are widely used by countries: 89 percent of countries reporting a reference level to the UNFCCC have used Open Foris, a set of free and Open-source solutions and platforms developed by the Food and Agriculture Organization of the United Nations (FAO) for accessing and analysing data. Improvements in forest monitoring are crucial to better understand forests' contribution to climate change mitigation and unlock climate finance.

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