Food and Agriculture Organization of the United Nations

Estimating emissions and removals from forest degradation

An overview of country experience

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Acronyms and abbreviations

ART-TREES	Architecture for REDD+ Transactions – The REDD+ Environmental Excellence Standard
ER-PD	emission reductions programme document
FCPF	Forest Carbon Partnership Facility
GCF	Green Climate Fund
GFOI	Global Forest Observations Initiative
IPCC	Intergovernmental Panel on Climate Change
NICFI	Norway's International Climate and Forest Initiative
RBP	results-based payment
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
UNFCCC	United Nations Framework Convention on Climate Change
VCS-JNR	Verified Carbon Standard – Jurisdictional and Nested REDD+ Framework

Chemical formulae/units

CO_2	carbon dioxide
CO_2eq	carbon dioxide equivalent
ha	hectare(s)
m	metre(s)
tC	tonne(s) of carbon
tCO_2eq	tonne(s) of carbon dioxide equivalent
yr	year

Executive summary

Estimating emissions and removals from forest degradation is important, yet challenging, for many countries. Where forest degradation is a major source of emissions, governments wish to cover it when reporting on their mitigation efforts (see Section 1.2); however estimating emissions from forest degradation is difficult.

There are three main challenges to accurately estimating emissions from degradation (see Section 1.3):

1. defining forest degradation and setting the scope for estimating carbon stock changes;

2. detecting and monitoring degradation using Earth observation data; and

3. estimating associated emissions and removals from field observation results.

This paper provides an overview of the methodological options available to countries to address these challenges.

There is much country experience available on estimating carbon stock changes from forest degradation and methodological options are emerging. Dozens of countries have already reported internationally on emissions from forest degradation (see Section 2). Most of the approaches can be grouped into three basic methodological options (see Section 2), although there remains much variability within those basic options regarding the definitions applied and the datasets used (see Section 3, Section 4 and Section 5):

1. *Areas and biomass stocks* has been the most widely used method. Countries measure the area of degradation events using high-resolution satellite imagery or other methods for activity data. Emission factors approximate the difference in average carbon stock over the medium term.

2. *Wood extraction versus regrowth* has been used several times in country reporting. Countries estimate the balance of gains and losses in forest biomass from the balance of wood extraction and increments.

3. *Direct measurement of changes in biomass stocks* has rarely been undertaken in developing countries' emissions reporting. The approach relies on directly observing carbon stock changes in permanent field plots in forest inventories.

How well methodological options work depends on the country context and the objectives (see Section 6.2). If there is a desire or a need to track emissions from specific drivers, this will dictate the estimation approach. Some estimation approaches can only be used where certain high-quality datasets are available, such as high-quality logging statistics or forest inventory with permanent sample plots. Remote sensing-based approaches struggle in forests that are highly variable – either seasonally or across the landscape – and persistent cloud cover and certain types of terrain can also cause challenges.

Definitions (see Section 3): Most countries set the scope for estimating emissions and removals from forest degradation by looking at forest degradation events within an assessment period (also known as activity-based estimation); other countries estimate all emissions and removals to occur within the assessment period, even if the relevant forest degradation events occurred earlier (also known as land-based estimation).

Moreover, definitions also differ by whether countries disaggregate emissions and removals by underlying processes, such as logging, fires, fuelwood collection and similar processes, or simply treat forest degradation in aggregate.

Earth observation (see Section 4): Most countries' forest monitoring relies on Earth observation to detect forest degradation. Expert human visual interpretation plays a key role, both for direct estimation and also for accuracy assessment of results of automated algorithms. Automated algorithms that have been successfully used to detect forest degradation include use of landscape fragmentation metrics, the use of granular scale of forest loss assessment, and the automated classification of satellite imagery using dense time-series analysis.

Field observation (see Section 5): Where estimating emissions from forest degradation relies on identifying degradation events through Earth observation, an approach is needed for estimating the associated emissions. This can be done by tracking carbon stock changes on an annual basis, or by estimating the expected carbon stock changes over a given time frame.

The choice of the approach for estimating forest degradation will also depend on the requirements of applicable carbon standards, related to the country context and what methods work well (see Section 6.1). Leading carbon standards and results-based payment (RBP) schemes include detailed requirements on the treatment of forest degradation that interested countries need to follow.

Recent and ongoing investments into data and analysis methods have helped improve forest degradation estimation, but further methodological work and continued effort will be needed. For example, detection of forest degradation in satellite images is a field of active research where advanced algorithms are being developed and applied to vast datasets (see Box 13). The many countries that have already reported on forest degradation have generated invaluable lessons learned on applying methods at a country level (see Section 2). Nonetheless, there are opportunities for further learning.

The following steps could lead to the improvement of measuring emissions from forest degradation:

1. Continue transparent sharing of information among countries and organizations involved in emission estimation and reporting, estimation approaches, and underlying datasets and methods, including the use of open-source software.

2. Continue improving availability of high-resolution imagery and sustaining the availability of such imagery in time, since it could enable identifying forest degradation more reliably.

3. Continue testing advanced remote-sensing approaches (high-density time-series analysis and others) to detect forest degradation – including the use of advanced datasets, such as utilizing laser or radar sensors.

4. Evaluate effectiveness of quality management in measuring emission reductions (notably from initial verifications and ongoing country efforts towards quality assurance in data collection) and insert lessons learned into measurement and reporting protocols, carbon standards technical guidance, and verification protocols.

5. Where possible, review technical guidance for emissions reporting, including carbon standards and donor requirements, to ensure that guidance responds to what is measurable rather than what is desirable from a policy perspective.

6. Work towards a consensus on treatment of postdegradation regrowth (whether or not it must be accounted for, whether to estimate annual or expected carbon stock changes, what the right time frames should be, and how this should be implemented in carbon standards).

7. Collect more and better information on dynamics of forest biomass emissions and removals over time, developing robust datasets on postdegradation regrowth patterns and applicable management regimes, which would improve the ability to separate the initial biomass loss during a degradation event from the gradual regrowth during the following years.

8. In some countries, strengthen datasets on forest degradation drivers, both regarding their occurrence, such as mapping logging, fire and others through Earth observation, and develop robust datasets on logging damages associated with harvests, on informal wood use to estimate emissions.

9. Test national forest inventories with permanent sample plots to quantify stock changes in forests, and emissions, from forest degradation.

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1. Introduction

1.1. CONTEXT FOR THIS DOCUMENT

Forest degradation is a key source of greenhouse gas emissions from forests. Global-scale estimates indicate that forest degradation can account for approximately one-quarter to three-quarters of the total emissions from deforestation and degradation combined; in some countries, it represents the most significant source of emissions from forests (Baccini *et al.*, 2017; Pearson *et al.*, 2017). Emissions from forest degradation, however, are particularly difficult to quantify, and for this reason, many countries still exclude it from the scope of their international reporting (FAO, 2022a).

Despite challenges, advances in data availability and processing capability provide new approaches for estimating emissions from forest degradation. High-performance computing platforms, such as the System for Earth Observation Data Access, Processing and Analysis for Land Monitoring (SEPAL) from the Food and Agriculture Organization of the United Nations (FAO), provide access to computing power sufficient for countries to run sophisticated algorithms on large datasets capable of detecting the finer-scale variations in tree canopy cover that characterize forest degradation (FAO, 2022b). High-spatial and temporal resolution satellite imagery, such as those that Planet Labs made freely available with support by the Norwegian International Climate and Forest Initiative (NICFI), also enhances analysts' ability to identify forest degradation. Meanwhile, countries continue strengthening their technical capabilities and collecting experience when including greenhouse gas emissions from forest degradation in international reporting (Neeff, van der Linden and Herrick, 2020).

This document is an effort to collect country experiences, take stock of technical progress on estimating emissions from forest degradation, and determine lessons learned. This document, which will be accompanied by a technical exchange will help enhance clarity on methodological options for estimating emissions from forest degradation. This process will address recipients and providers of technical assistance; going forward, the outcomes will help underpin well-founded technical advice to countries on methodological options and provide direction to future research work and related donor investment.

There is no single best methodological approach for quantifying emissions from forest degradation. Rather, there are various options that can be deployed according to a country's circumstances. In this document, we aim to present and synthesize the wealth of lessons learned from available country cases covering a variety of conditions.

This document was made possible through efforts by FAO and its partners, such as the United States Forest Service's SilvaCarbon programme. A request for input on this document was circulated through the Global Forest Observations Initiative (GFOI) to engage the technical community interested in and leading the advancements in estimating emissions from forests in a context of country-scale mitigation efforts. In early 2023, the GFOI will bring together a group of countries for a South–South exchange on forest degradation under leadership of the United States Forest Service's SilvaCarbon programme in cooperation of FAO – this document will help structure the exchange.

Box 1. A definition of *"forest degradation"*?

This paper is concerned with forest degradation in the context of estimating emissions and removals from forests. The discussion does not address the enormous complexities surrounding the concept of degradation regarding forest structure, biodiversity, ecosystem services, etc.[a] Much work on such topics has been undertaken in other contexts, for example within FAO's Global Forest Resource Assessment,[b, c] and FAO is currently also leading a discussion to define "forest degradation" within the Forest Resource Assessment process.[d]

In this paper, however, "forest degradation" merely refers to a category of emissions and removals associated with carbon stock changes in forests, following terminology from the international climate change negotiations.[e] It is important to note that the occurrence of emissions from forest degradation does not mean that forests are "degraded" – if one understands the term to imply a depletion of indicators such as forest structure, biodiversity and others.

This paper does not propose its own definition of forest degradation. Rather, it summarizes how countries have used this term when reporting on emissions and removals from forests in several contexts.

Notes: [a] Ghazoul, J., Burivalova, Z., Garcia-Ulloa, J. & King, L.A. 2015. Conceptualizing Forest Degradation. *Trends in Ecology & Evolution*, 30(10): 622-632. https://doi.org/10.1016/j.tree.2015.08.001
[b] FAO. 2020a. *Global Forest Resources Assessment 2020*: Main report. Rome. https://doi.org/10.4060/ca9825en
[c] FAO. 2011. *Assessing forest degradation: Towards the development of globally applicable guidelines*. Forest Resources Assessment Working Paper No. 177. Rome, Italy. www.fao.org/3/i2479e/i2479e00.pdf
[d] FAO. 2022. *Committee on Forestry,* 26th Session: Report. Rome. https://www.fao.org/3/nk728en/nk728en.pdf
[e] The UNFCCC refers to Reducing Emissions from Deforestation and Forest Degradation, as well as the sustainable management of forests and the conservation and enhancement of forest carbon stocks in developing countries (REDD+).

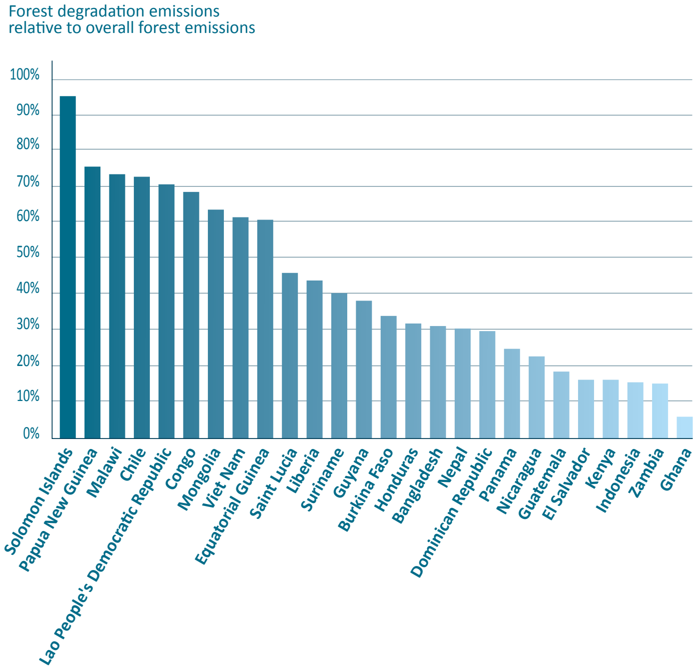
Source: Authors' elaboration.

1.2. IMPORTANCE TO COUNTRIES

Countries around the world are working to include emissions from forest degradation in their national forest monitoring systems (FAO, 2022a). Forest degradation is a major source of emissions that countries wish to cover when reporting on their mitigation efforts. Also, where robust information on forest degradation is available, it can be used to underpin policy instruments that address forest degradation. Finally, including forest degradation is also mandatory in several international reporting contexts.

In many countries, emissions and removals from forest degradation are significant; in some countries, they amount to the largest source of emissions (see Figure 1). Global estimates of the share of forest emissions that originate from forest degradation range from 25 percent (Pearson *et al.*, 2017) to almost 70 percent of carbon losses (Baccini *et al.*, 2017). An assessment of forest reference emissions levels that countries reported to the United Nations Framework Convention on Climate Change (UNFCCC) found 34 percent of forest emissions to come from degradation (FAO, 2022a).

Figure 1. Emissions from forest degradation in selected countries as a percentage of total forest emissions in UNFCCC reference level submissions



Notes: Where countries have provided updates, this shows most recent submissions. The list of countries including forest degradation in the scope of UNFCCC submissions is slightly longer than displayed in this chart. Excluded were submissions that do not disaggregate emissions per activity, that do not include all emissions from degradation, or that report net removals from degradation.

Source: Authors' elaboration using countries' UNFCCC submissions.

High-quality datasets can be an important enabler of governmental efforts to address deforestation and forest degradation (FAO, 2020). Some countries have developed innovative policy instruments from strong datasets relevant for deforestation (Neeff *et al.*, 2020). Indeed, robust datasets are easier to generate for deforestation than forest degradation. If the data situation improved, then this could presumably also strengthen the countries' ability to address forest degradation. For example, in 2021 and 2022, the European Commission has been working to implement new regulation on imported deforestation and introduce a novel due diligence requirement for several agricultural commodities (European Commission, 2021). When placing imported goods on the market, proof might need to be provided that their production did not entail deforestation or forest degradation. Any such proof will only be as sound as the datasets that support it.

In most reporting contexts, including forest degradation is a mandatory requirement (see Section 6.1). There is some flexibility when reporting under the UNFCCC and to the Green Climate Fund (GCF) with its pilot programme for results-based payments, as countries commit to a process of stepwise improvement. But carbon finance initiatives that also issue carbon credits are less amenable to country circumstances and will usually require reporting on forest degradation. This paper covers Verra's Verified Carbon Standard (VCS) with its modality for Jurisdictional and Nested REDD+ (JNR),[1] The REDD+ Environmental Excellence Standard (TREES) by the Architecture for REDD+ Transactions (ART),[2] and the Forest Carbon Partnership Facility's (FCPF) Carbon

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[1] For more information, see https://verra.org

[2] For more information, see www.artredd.org

Fund[3]. As the options to access carbon finance grow more concrete for countries with jurisdictional mitigation programmes, there is also an increasing need for robust estimates of forest degradation emissions.

1.3. CHALLENGES

Estimating emissions from forest degradation is difficult. Reference level submissions to the UNFCCC illustrate that countries are struggling with forest degradation: while 55 of the 56 countries that have submitted a reference level to the UNFCCC included emissions from deforestation, only 33 countries included emissions from forest degradation (FAO, 2022a). There are three main challenges to accurately estimating stock changes from degradation: (1) defining forest degradation and setting the scope for estimating carbon stock changes; (2) detecting and monitoring degradation using Earth observation data; and (3) estimating associated emissions and removals from field inventory results (see Goetz *et al.*, 2015).

Forest degradation is hard to define because biomass gains and losses are dynamic processes (Thompson *et al.*, 2013) – even severely degraded forests could, eventually, recover if left undisturbed for a long time. Because of this, definitions need to consider time frames for carbon stock changes. Defining forest degradation is especially challenging where ecosystems naturally include low and high density forests (Thompson *et al.*, 2013). Any conclusion on whether forests are *"degraded"* compared to average conditions would depend on the spatial and temporal scale considered (see Figure 2). Often, only limited information is available about this dynamic process and there is considerable variation among countries' approaches to defining the scope for estimating emissions and removals.

Figure 2. Difficulties in defining forest degradation

Is this temporary? Gradual biomass recovery after a degradation event

Is this just local variation? Naturally occurring biomass differences within forests

Source: Authors' elaboration.

The definitional complexities translate into difficulties in identifying degradation events through Earth observation. Defining forest degradation needs to address all the difficulties already inherent to national definitions of *"forest"* (distinguishing land use from land cover, codifying vegetation morphology by recurring to parameters such as canopy density per area unit, etc.). While forest degradation can occur gradually or rapidly, it is often a diffused process, further increasing difficulties. The ability to detect degradation requires Earth observation data and processing techniques able to detect subtle changes over time. In some cases, for

[3] For more information, see www.forestcarbonpartnership.org

example, where forests include very low height thresholds or where areas are very small, detecting the more subtle changes associated with forest degradation might be almost impossible.

Even if degradation events can be reliably identified, it is hard to determine the associated emissions and removals from field observations. This requires inferring carbon stock changes over an assessment period of usually several years. Difficulties increase where degradation is not a one-off event but results from long-term pressure on the forest with repeated degradation events. Emissions and removals from forest degradation can vary greatly depending on the time frame considered; often, information about long-term carbon stock dynamics will be incomplete.

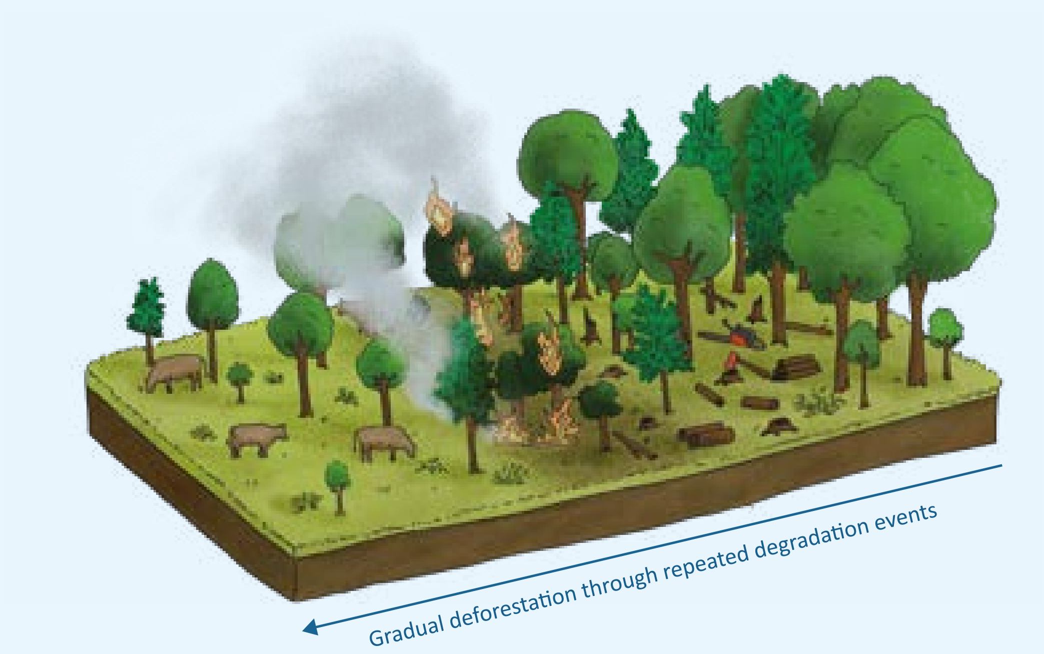
Box 2. Where could it be more efficient to track deforestation rather than forest degradation?

In some locations, degradation will be a precursor of deforestation. Forest might slowly degrade under the influence of grazing, recurrent burning, and unsustainable use, retaining minimum vegetation cover for a long time until at some point most trees are gone and degradation turns into deforestation.

Deforestation could be far easier to detect than the gradual forest degradation process – where one is the precursor to the other, it might be efficient to focus attention on accurately estimating deforestation emissions.

Often forest degradation is driven by processes entirely separate from deforestation and then needs to be quantified separately.

Degradation as a precursor of deforestation



Source: Authors' elaboration.

2. Methodological options

Albeit difficult, dozens of countries have already estimated and reported greenhouse gas emissions from forest degradation – 33 countries have reported such emissions to the UNFCCC (FAO, 2022a). Most of the methods used in this reporting can be broadly grouped into three approaches for estimating emissions from forest degradation.[4] These approaches reflect underlying definitions adopted and come with typical sets of corresponding activity data and emission factors (see Table 1).

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4 Countries have experimented with other ways to measure emissions from forest degradation. Other activity-based methods include stump counting in forest inventory plots (the Lao People's Democratic Republic), lorry truck counting to estimate the extent of illegal logging (Ghana), and applying a spatial demand-supply model to assess net carbon losses from fuelwood harvesting (Nepal and Ghana). There are also other land-based approaches including through using the gain-loss method.

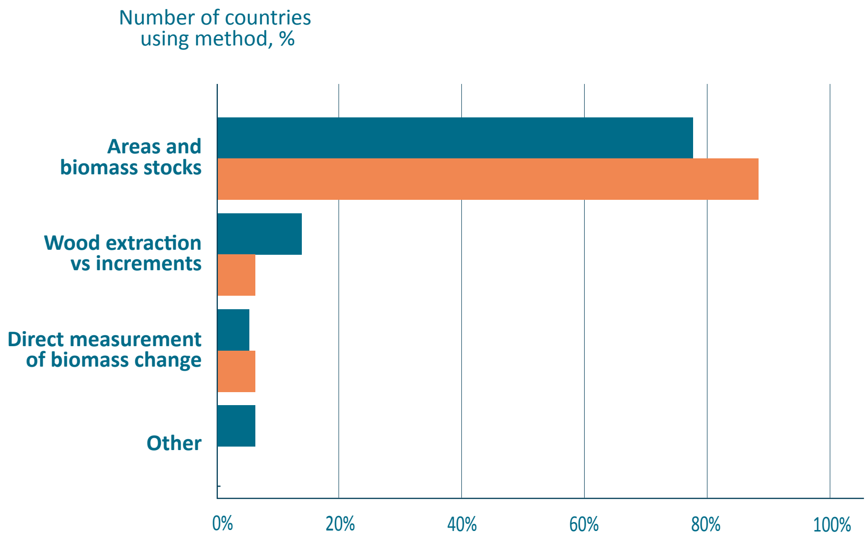
Table 1. Three principal approaches that countries use for estimating emissions and removals from forest degradation

Estimation approach	Definition	Activity data	Emission factors
Areas and biomass stocks	Aggregate emissions and removals of degradation events, where the events occur in the assessment period	Forest degradation area estimates based on various combinations of sampling and automated mapping methods	Stock changes associated with the degradation events and the subsequent regrowth that the area measurements reflect, typically measured in a field inventory
Wood extraction versus regrowth	Emissions and removals from logging, where the events occur in the assessment period	For losses, statistics on logging volumes; for gains, depending on available removal factors, area of post-degradation regrowth	For losses, a range of expansion factors to apply to extracted wood estimates, notably for logging damage; for gains, either area-based regrowth factors, or information on portion of biomass recovery
Direct measurement of changes in biomass stocks	Aggregate emissions of forest that remains forest during the assessment period, where net biomass decreases	Direct measurement of changes in biomass stocks through repeated field measurement of (ideally permanent) sample plots	

Source: Authors' elaboration based on Neeff, T., van der Linden, M. & Herrick, M. 2020. *Choices in Quantifying Carbon for Jurisdictional REDD+: Overview from the Forest Carbon Partnership Facility*. World Bank, Washington, D.C. https://openknowledge.worldbank.org/handle/10986/35707

The majority of countries are estimating emissions from forest degradation through area estimates multiplied by a factor of emissions per area unit. Between 10 percent and 15 percent of countries are estimating degradation emissions through wood extraction and increments. Around 5 percent of countries use direct measurements of biomass change (see Figure 3).

Figure 3. Country approaches to estimating emissions from forest degradation



Notes: Only some countries included forest degradation. For the FCPF Carbon Fund, 17 out of 18 countries included forest degradation; for UNFCCC, 33 out of 56.

Source: Authors' elaboration based on country submissions.

Areas and biomass stocks: This approach is a modification of the gain-loss method for forestland remaining forestland from the Intergovernmental Panel on Climate Change (IPCC).[5] This is an activity-based method (see Section 3) that treats forest degradation emissions on aggregate. Carbon stock change from forest degradation is estimated from the loss and gain of carbon. Since forest degradation can be deemed to occur in forest areas with a net biomass decrease, the area of degraded forest (i.e. the activity data) is simply the area of all known degradation events in the assessment period. The net gains and losses per area unit (i.e. the emission factor) are taken to correspond to the difference between carbon stocks before and after a degradation event. The following basic equation is applied:

[Emissions from forest degradation] = [Forest area of degradation events] × { [Per-hectare carbon stock before degradation] − [Per-hectare carbon stock after degradation] }

Care must be taken when selecting activity data and emission factors. Since it is an activity-based method (see Section 3), it is key that area measurements reflect the occurrence of *degradation events* in the assessment period (a transition between forest types), rather than aim to estimate the *total area of degraded forest* during any point in time (the forest type status).[6] (The area of degraded forest would be of interest when using *Direct measurement of changes in biomass stocks* or other land-based methods.) Measurements can be made using various combinations of sample-based assessments and mapping efforts (see Section 3.2). Emission factors will typically be built from the difference between average stock of non-degraded forest and degraded forest from field measurements, reflecting average carbon stock differences (see Section 5).

5 See Equation 2.4 in 2019 refinement to the 2006 IPCC guidance, page 2.10 in Volume 4; https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/4_Volume4/19R_V4_Ch02_Generic%20Methods.pdf#page=10

6 For example, if an assessment period was 2017–2019, then the area of degradation events would, in theory, correspond to area of degraded forest in 2019 minus area of degraded forest in 2017, while the total area of degraded forest at the end of 2019 will necessarily be larger.

Wood extraction versus regrowth: This approach is also a modification of the IPCC's gain-loss method,[7] where carbon stock change is the difference between gains of carbon and loss of carbon. This is an activity-based method (see Section 3) for impacts of logging. The estimate of emissions from forest degradation is a measure of the loss of carbon based on wood-use statistics as activity data and a measure of logging damage as an emission factor. This is the basic equation:

[Emissions from forest degradation through logging] = [Amount of wood extracted] × [Logging damage factor] − [Post-logging regrowth]

This approach necessitates accurate wood-use statistics to produce robust estimates. In some contexts, this could be difficult. For logging statistics, data quality could depend on the strength of local forest management arrangements, such as reporting procedures and monitoring. Building emission factors can be difficult because they need to factor in not only the carbon in harvested trees, but also collateral damage from wood extraction that could greatly depend on harvesting techniques, forest type and other factors, which could therefore be hard to estimate in a robust manner (Pearson *et al.*, 2014). Moreover, it is important to factor in both the initial loss of carbon stock upon logging and the gains from post-logging regrowth. There are several ways to do this, either using information on the area that underwent logging and the average increment rate of regrowing forest, or detailed information on the portion of biomass expected to recover over a given time frame (see Section 5).[8]

There are other important drivers of forest degradation beyond logging (Hosonuma *et al.*, 2012). The approach *Wood extraction versus regrowth* is therefore often combined with approaches for estimating emissions associated with other drivers. For example, much work has been done to estimate emissions associated with fire or with fuelwood collection which often generate significant amounts of emissions (see Box 6 in Section 3). This paper discusses emissions associated with logging in more detail since countries have frequently reported on them.

Direct measurement of changes in biomass stocks: This approach is an application of the IPCC's stock-difference method.[9] This is a land-based approach (see Section 3) that estimates stock changes that occur during an assessment period.[10] Usually, this approach requires repeated inventories, usually field inventories, with consistent methods to accurately quantify overall carbon stocks at more than one time point. The following basic equation underlies estimation:

[Emissions from forest degradation] = { [Total carbon stock at time 2] − [Total carbon stock at time 1] } ÷ [time difference between time 1 and 2]

The resource requirements for collecting regular national forest inventory results can be significant, both in terms of funding needs and staff required; even if repeat inventories are being conducted, the datasets may be too small to generate a precise estimate of (usually relatively small) carbon stock changes. This is especially a problem when temporary sample units are used, while uncertainties could be much smaller when using

7 See Equation 2.4 in 2019 Refinement to the 2006 IPCC guidance, page 2.10 in Volume 4; https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/4_Volume4/19R_V4_Ch02_Generic%20Methods.pdf#page=10

8 Conversely, other pertinent information that may often be contained in forest management plans, such as related to cutting cycles, basal area distribution or minimum cut diameter, is not usually incorporated when determining forest degradation and emissions and removals.

9 See Equation 2.5 in 2019 refinement to the 2006 IPCC guidance, page 2.10 in Volume 4; https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/4_Volume4/19R_V4_Ch02_Generic%20Methods.pdf#page=10

10 Land-based approaches can also be implemented using the gain-loss method, but this is not discussed in detail in this paper.

permanent sample units. There are currently no developing countries employing permanent sample units to measure forest degradation emissions in a REDD+ context.

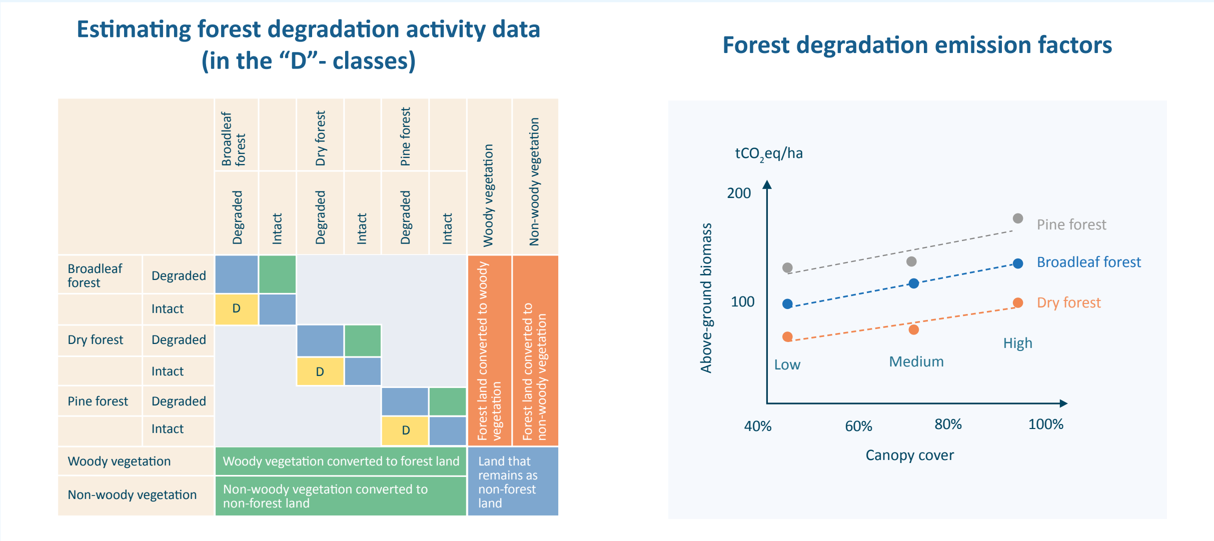
Box 3. Areas and biomass stocks, the Dominican Republic

In their 2020 reference level submission to the UNFCCC,[a] the Dominican Republic measured emissions from forest degradation (as well as removals from forest recovery) by using a crown cover proxy that could be measured in satellite imagery and that correlated with biomass stock differences.

The area of forest degradation was estimated using a systematic grid of sample units for visual interpretation of satellite imagery. For all areas of forest land remaining forest land, interpreters measured areas with canopy cover changes. Any observed canopy cover change was assigned to a transition between three broad degradation classes – low, medium, high – according to their canopy cover.

To establish the emission factors, the Dominican Republic estimated biomass from measurements taken for its national forest inventory. By grouping inventory plots into low, medium and high canopy cover classes, a linear regression was built to relate average canopy cover to average biomass. Emission factors were then selected based on the expected associated biomass change as per the regression.

The Dominican Republic's approach for estimating forest degradation emissions



Source: Modified and simplified from the 2020 reference level submission to the UNFCCC.

Using this approach based on correlating biomass measurements with canopy cover measurements entails a risk of bias. The emission factors should reflect the long-term average decrease of carbon stock upon forest degradation rather than the initial drop in biomass during the degradation event (see Section 5), but there is a risk that the used approach more closely relates to the initial drop in biomass since it is built directly off the correlation to crown cover, which is invariably observed during the degradation event.

Random uncertainties are also high because biomass stocks need to be inferred from observed canopy cover to then subsequently derive biomass stock differences. The submission explains that uncertainties in inferring biomass stock changes from the regression model amount to around 94 percent to 175 percent (using a mean-squared error estimate), and that the resulting uncertainties of emissions from forest degradation and removals from forest recovery amounts to 64 percent and 117 percent, respectively (the half-width of the 95 percent confidence level).

The above discusses the approach taken in a 2020 submission to the UNFCCC; in a 2022 submission to the UNFCCC, the Dominican Republic updated the emission factor calculation. The new approach estimates degradation emissions through a combination of volume of extracted wood and an assessment of area burned and intensity of burning. The new approach results in degradation emissions that are 11 percent higher compared to the previous submission for the same historical period (2006–2015).

Notes: [a] For more information, see https://redd.unfccc.int/info-hub.html

Source: Authors' elaboration.

Box 4. Wood extraction vs regrowth, Guyana

Guyana has reported on emissions from forest degradation in different contexts, including to the UNFCCC,[a] its donors[b] and ART-TREES.[c] Guyana's forest monitoring system quantifies these emissions based on available statistics of wood extraction and data on collateral logging damages.

Guyana used high-quality, auditable databases for estimating volume of wood extraction.[d] For legal logging, volume data is drawn from the Guyana Forestry Commission's Management Information System that records all logging permits. For illegal logging, a separate database collects information on infractions, regularly monitored at 36 field stations.

Emission factors for logging relate total biomass damaged to the volume of timber extracted, factoring in the biomass of harvested trees, as well as collateral logging damage and damage from skidding trees, where the biomass loss amounts to almost three times the biomass in harvested volume (Box 15).

In Guyana, no measurement of carbon gains is undertaken, although some level of post-logging regrowth must be expected. The key paper that Guyana used as a source for forest degradation emission factors suggests that forest regrowth will not always accelerate after logging; [e] therefore, carbon gains would not need to be disaggregated from general background forest growth. It is a topic of scientific debate how fast forests regrow after logging (see Section 5).

Notes: [a] For more information, see https://redd.unfccc.int/info-hub.html
[b] For more information, see https://forestry.gov.gy/mrvs-interim-measures-reports
[c] For more information, see https://art.apx.com
[d] Guyana's MRVS report 2021, referenced in the ART-TREES registration document, https://forestry.gov.gy/wp-content/uploads/2022/06/Guyana-MRVS-Report-Year-2021-Final.pdf
[e] Pearson, T.R.H., Brown, S. & Casarim, F.M. 2014. Carbon emissions from tropical forest degradation caused by logging. Environmental Research Letters, 9(3): 034017. https://doi.org/10.1088/1748-9326/9/3/034017

Source: Authors' elaboration.

Box 5. Direct measurement of changes in biomass stocks, Viet Nam

For several decades, Viet Nam has maintained a sophisticated forest monitoring system, which has enabled reporting to the UNFCCC,[a] as well as participation in the FCPF Carbon Fund.[b] More recently, Viet Nam has also decided to participate in ART-TREES.[c] For quantifying emissions from forest degradation, Viet Nam has relied on a plot-based inventory, which has been conducted in approximate five-year intervals.

Viet Nam used a forest stratification where areas of the forest types were measured using a set of forest cover maps. The corresponding per-ha carbon stocks at both time points were derived from the national forest inventory results. Since the plot-based inventory has been conducted periodically, changes can be identified. For example, the biomass in Evergreen broadleaf – rich forest decreased from 146 tC/ha +/− 5% in Cycle III (2005) to 140 tC/ha +/− 3% in Cycle IV (2010), with an evident change that amounted to 6 tC/ha, or 1.2 tC/ha/yr.[d]

Carbon stock estimates with uncertainty estimates for four national forest inventory cycles

Forest types	Cycle I	Cycle II	Cycle III	Cycle IV
1. Evergreen broadleaf – rich	150 ± 4%	152 ± 3%	146 ± 5%	140 ± 3%
2. Evergreen broadleaf – medium	73 ± 1%	73 ± 1%	75 ± 1%	75 ± 1%
3. Evergreen broadleaf – poor	32 ± 3%	32 ± 2%	32 ± 3%	32 ± 3%
4. Evergreen broadleaf – regrowth	32 ± 6%	30 ± 5%	26 ± 5%	26 ± 6%
5. Deciduous	40 ± 14%	36 ± 5%	32 ± 5%	31 ± 8%
6. Bamboos	14 ± 10%	13 ± 9%	13 ± 7%	15 ± 11%

Notes: Living biomass in tC/ha.

Source: Viet Nam's reference level submission to the UNFCCC. For more information, see https://redd.unfccc.int/info-hub.html

Notes: [a] For more information, see https://redd.unfccc.int/info-hub.html
[b] For more information, see https://www.forestcarbonpartnership.org
[c] For more information, see https://www.artredd.org/art-registry
[d] Although they are not being reported in Viet Nam's submission to the UNFCCC, the uncertainties in applying this approach with temporary sample plots must be expected to be considerable. The observed −6 tC/ha change between Cycle III and Cycle IV in Evergreen broadleaf – rich forest comes with an uncertainty of 140 percent. Using Equation 3.2 in Chapter 3 of the 2006 IPCC guidance, the uncertainty would amount to √ { (146 tC/ha × 5%)2 + (140 tC/ha × 3%)2 } / 6 tC/ha = 140%.

Source: Authors' elaboration.

3. Defining forest degradation when estimating emissions and removals

Countries have found a variety of ways to address the definitional complexities related with emissions and removals from forest degradation (see Section 1.3), which are reflected in their use of basic estimation approaches (see Section 2), how these set the scope of estimation, and how they track emissions and removals over time.

3.1. SETTING THE SCOPE

In the context of estimating emissions, it is common practice to define REDD+[11] activities, including forest degradation, by reference to categories from the guidance by the IPCC on national greenhouse gas inventories (FAO, 2022a; GFOI, 2020). Accordingly, emissions from forest degradation are emissions from forest land remaining forest land where there is a net loss of carbon stocks (FAO, 2022a; Herold *et al.*, 2011) making it less easily detectable through remote sensing. Although we anticipate the use of the IPCC guidance under the United Framework Convention on Climate Change. This definition allows a clear separation of forest degradation from changes between forest land and non-forest land (i.e. deforestation and reforestation).

There are at least two further definitional distinctions that are key. First, most countries use activity-based methods and others use land-based approaches. The activity-based approaches consider activities that occur *during* the assessment period (although the associated emissions and removals might occur *during and after* the assessment period). Both the approaches *Areas and biomass stocks* and *Wood extraction versus regrowth* are activity-based; however, other countries use land-based approaches that consider all emissions and removals from lands falling into a certain category, regardless of when the event occurred that caused them. The approach *Direct measurement of changes in biomass stocks* is land based (there are other land-based estimation approaches that this paper does not discuss in detail).

In the context of mitigation programmes, countries have mostly opted for activity-based methods and for treating forest degradation emissions on aggregate (see Section 2). Of principal interest is estimating the full greenhouse gas impact of forest degradation and the full mitigation result of mitigation measures to address forest degradation. Land-based methods stretch reporting over long time frames when emissions and removals actually occur, while activity-based methods usually count emissions and removals in the year of the degradation event, depending on how emission and removal factors are defined (see Section 5).

Where countries use activity-based methods, a second key definitional difference relates to whether emissions and removals are disaggregated by drivers or treated in aggregate. Sources of emissions and removals differ between countries and could include logging, fires, fuelwood collection and similar processes (Hosonuma *et al.*, 2012); some countries report emissions accordingly (see Box 6). Estimating emissions for a given driver will require collecting activity data and emission factors accordingly. For example, there is a well-defined estimation approach for emissions from logging (see Section 2); however, many countries do not attempt to disaggregate estimation by drivers and simply treat forest degradation emissions in aggregate. Activity data and emission factors could then also be aggregate (although possibly still disaggregated by forest types

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11 The five REDD+ activities are: deforestation, forest degradation, enhancement of carbon stocks, conservation of carbon stocks, and sustainable forest management.

or similar) and directly relate to the reporting categories in the guidance by the IPCC and associated REDD+ activities (see Box 7).

Box 6. Quantifying carbon stock losses and gains separately by driver, Suriname

Suriname has submitted two forest reference emissions levels to the UNFCCC in 2018 and 2021,[a] which include a detailed quantification of emissions from forest degradation.

Emissions from forest degradation are disaggregated as follows:

- Emissions caused by roundwood logging (further disaggregated by extracted logs, logging damages and logging infrastructure)
- Emissions caused by fuelwood extraction
- Emissions caused by shifting cultivation

Projected annual emissions in Suriname's forest reference emission level

Year	Deforestation	Degradation				Total
	Total deforestation	Roundwood	Fuelwood	Shifting cultivation	Total degradation	Total projected emissions
2020	8 420 597	4 606 703	215 503	766 090	5 588 292	14 008 889
2021	8 775 256	4 857 731	208 413	770 834	5 836 974	14 612 231
2022	9 129 915	5 108 760	201 323	775 578	6 085 657	15 215 572
2023	9 484 574	5 359 788	194 233	780 321	6 334 339	15 818 913
2024	9 839 233	5 610 817	187 143	785 065	6 583 022	16 422 255

Notes: Emissions in tCO_2eq/yr.

Source: Suriname's reference level submission to the UNFCCC.

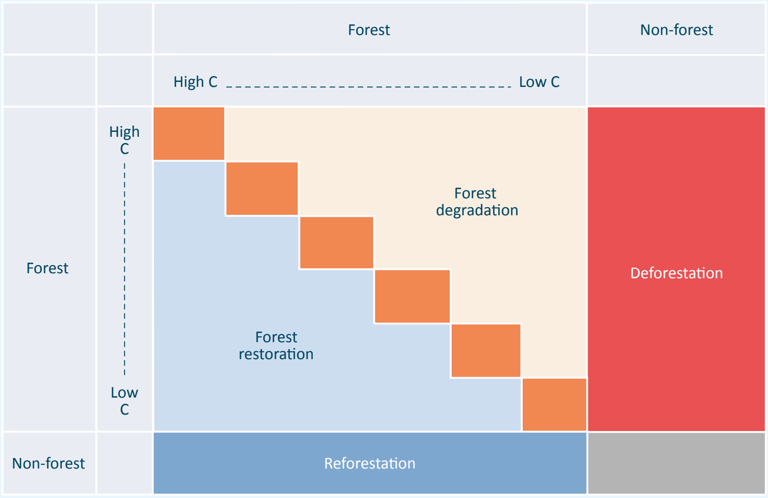
Notes: [a] For more information, see https://redd.unfccc.int/info-hub.html

Source: Authors' elaboration.

Box 7. Aggregate treatment of higher or lower carbon stocks to quantify forest degradation, Viet Nam

Viet Nam has reported on forest-related mitigation efforts in the context of the UNFCCC and the FCPF Carbon Fund, and recently also expressed interest in ART-TREES (see Box 5). The definition of the REDD+ activities is undertaken with reference to which lands are considered "*forest*" and "*non-forest*", and with reference to the higher or lower carbon stocks in forests.

Definition of REDD+ activities in Viet Nam's reference level submission to the UNFCCC



Notes: Simplified from original.

Source: Viet Nam's reference level submission to the UNFCCC.

Source: Authors' elaboration.

3.2. TRACKING ANNUAL VS EXPECTED CARBON STOCK CHANGES

Estimation can be undertaken to track carbon stock changes *on an annual basis*, or by estimating the expected carbon stock changes over a given time period (see Table 2 and Figure 4).

Table 2. Two approaches for estimating annual or expected carbon stock changes associated with forest degradation

Description	Approach	Output	Objective
Tracking carbon stock changes annually	Account for emissions and removals when they occur	Annual estimates over a multi-year period	Estimation of current emissions in a given year, enables most accurate reporting on actually occurring emissions, common in greenhouse gas inventory reporting
Estimating expected carbon stock changes over a given time period	Account for emissions and removals expected to be associated with a degradation event	One-off estimate, to accrue in the year of the degradation event	Estimation of expected emissions from activities, enables estimating emissions reductions against a historical average baseline

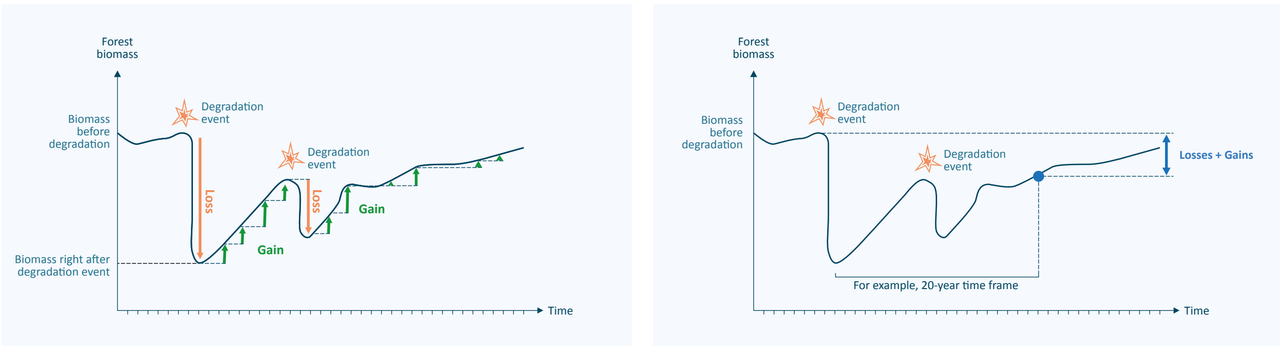
Source: Authors' elaboration.

Tracking carbon stock changes annually: Quantifying emissions from forest degradation requires taking into account both the initial loss of carbon during the actual degradation event, and the gradual carbon gains as forests recover during the following years. The most correct way to do this is by accounting for such carbon stock changes when they occur, that is, through annual estimates (this is the approach foreseen in the guidance by the IPCC for national greenhouse gas inventories).

Estimating expected carbon stock changes over a given time frame: The degree of forest degradation depends on the time frame considered because biomass gains and losses are dynamic processes over time (see Section 1.3). Over a long enough time frame, any shortfall in biomass stocks may grow back – but further degradation events may also be expected to occur over the years. The estimate of carbon stock changes from forest degradation needs to factor in both the initial loss of biomass during the degradation event *and also the subsequent gain when forests grow back.*[12] Estimating the expected carbon stock changes, rather than the actual carbon stock changes during an assessment period, is not foreseen in the guidance by the IPCC for national greenhouse gas inventories.

Figure 4. Sketch of biomass changes after several degradation events and two approaches for quantifying associated carbon gains and losses

Tracking carbon stock changes annually | **Estimating expected carbon stock changes over a given time period**



Source: Authors' elaboration.

When estimating emission reductions is the objective, countries have rarely opted for tracking carbon stocks on an annual basis and have mostly estimated expected carbon stock changes. There are several reasons for this. Rarely are consistent long time series available that enable tracking the age of forest cohorts over long time frames. How to treat legacy removals that originate from forest degradation that occurred before assessment began also represents a difficult question. Even where these difficulties could be overcome, when estimating emission reductions of mitigation actions, the full greenhouse gas impact of forest degradation is of chief interest and the chosen approach needs to be adequate. It may sometimes be seen as inappropriate to fully account for losses (upon the degradation event), yet stretch gradual gains out over decades (when they actually occur), as this obscures the expected greenhouse gas impact from forest degradation. Because

12 In estimating carbon stock changes (whether estimating expected changes or estimating annual changes), it is essential to cover both the initial carbon loss during the degradation event and the subsequent gain when forests grow back. Decoupling the estimation of gains from losses is problematic because degradation events cause both. Where the scope of estimated emission reductions from mitigation efforts includes only the losses, there is a risk of overestimating emission reductions because some of the losses could be offset by gains during forest regrowth.

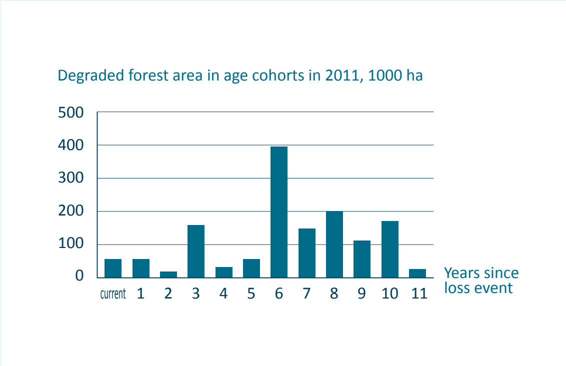
of this, countries have mostly opted to build emission factors from considering long-term average carbon stocks. However, there is no consensus on this question, not even in the leading carbon standards.[13]

Box 8. Tracking carbon stock changes annually: The Indonesian National Carbon Accounting System

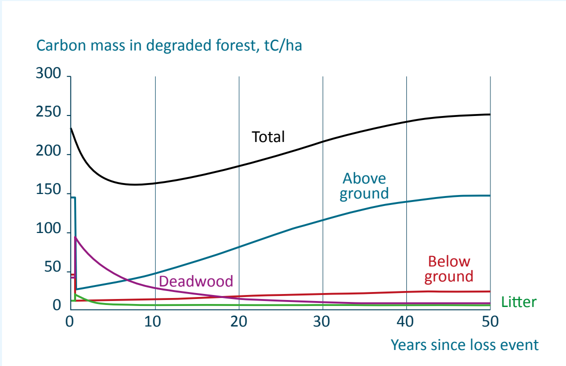
The Indonesian National Carbon Accounting System (INCAS) relies on a bookkeeping model where remote sensing is set up to identify and track age cohorts of forest degradation areas, from occurrence of the initial degradation event over their gradual recovery. The information on age cohorts can then be brought together with information on carbon stock changes over age postdegradation to yield estimates of annual carbon losses and gains.

Data inputs for the Indonesian National Carbon Accounting System (INCAS) approach to estimating carbon stock gains and losses from forest degradation in Central Kalimantan province

Bookkeeping of degradation area and its age after degradation events



Carbon stock as a function of age after a degradation event[a]



Source: Authors' elaboration based on data provided by INCAS

Notes: [a] MoEF (Ministry of Environment and Forestry). 2015. Standard Methods for Estimating Greenhouse Gas Emissions from Forests and Peatlands in Indonesia - Indonesian National Carbon Accounting System (INCAS), Version 2. Ed. Ministry of Environment and Forestry, Jakarta, Indonesia.

Source: Authors' elaboration.

[13] The VCS-JNR requires using a long-term average carbon stock when quantifying emissions from forest degradation. ART-TREES includes both options to use either a long-term average carbon stock or to account for annual changes as they occur.

Box 9. Estimating expected carbon stock changes, the Congo

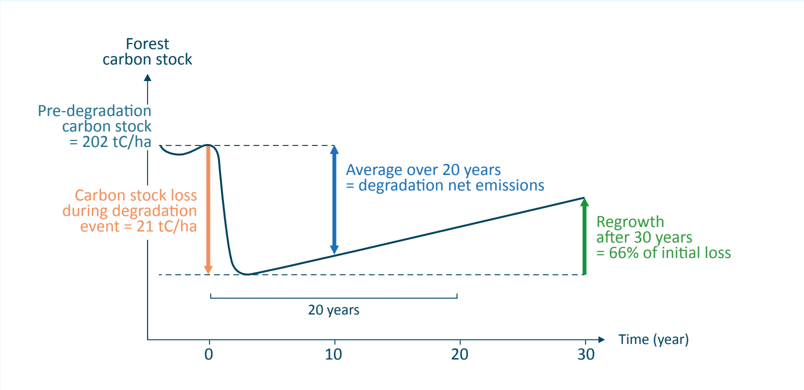
When working towards submitting an expression of interest to the Coalition for Lowering Emissions by Accelerating Forest finance (LEAF),[a] the Congo updated its approach to estimating emissions from forest degradation.

The improved approach had to consider both the initial carbon stock loss and also regrowth, which requires defining the assessment period. The guidance by the IPCC refers to a default of a 20-year assessment period until vegetation attains a new equilibrium in carbon stocks after disturbance. Carbon standards also include recommendations on such time frames.[b]

For the LEAF submission, the Congo followed the 20-year time frame, drawing on a combination of information from previous work and scientific studies:

- Average carbon stock of not degraded forest = 202 tC/ha[c]
- Carbon stock loss during the degradation event = 21 tC/ha[d]
- Regrowth over 30 years after the degradation event = 66 percent[e]

The Congo's emission factor for emissions from forest degradation



Notes: [a] For more information, see https://leafcoalition.org
[b] ART-TREES refers to a 20-year period for defining "long-term average post-emission carbon stock", but points out also that a full rotation shall be used in case of cyclical systems. VCS-JNR requires using the "average state of carbon stock in the degraded forest".
[c] Umunay, P.M., Gregoire, T.G., Gopalakrishna, T., Ellis, P.W. & Putz, F.E. 2019. Selective logging emissions and potential emission reductions from reduced-impact logging in the Congo Basin. Forest Ecology and Management, 437: 360-371. https://doi.org/10.1016/j.foreco.2019.01.049
[d] Umunay, P.M., Gregoire, T.G., Gopalakrishna, T., Ellis, P.W. & Putz, F.E. 2019. Selective logging emissions and potential emission reductions from reduced-impact logging in the Congo Basin. Forest Ecology and Management, 437: 360-371. https://doi.org/10.1016/j.foreco.2019.01.049
[e] From the UNFCCC reference level.

Source: Authors' elaboration.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4. Detecting forest degradation through Earth observation

A variety of approaches have been found suitable to identify degraded forest or degradation events in satellite imagery, and thus may suit methodological approaches for estimating greenhouse gas emissions. These classification approaches range from expert human visual interpretation to advanced automated computer algorithms applied to extremely large datasets (see Table 3).

Table 3. Overview of approaches for identifying forest degradation in satellite imagery

Description	Approach	Output	Objective
Sample-based area estimation (see Box 10)	Visual interpretation (often in combination with other methods for stratifiers)	Area statistics	Area estimation
Landscape fragmentation metrics as a proxy of forest degradation (see Box 11)	Automated algorithm (e.g. landscape fragmentation)	Map	Stratification map, support to visual interpretation, in few cases area estimation
Using granular scale of forest loss assessments to identify forest degradation (see Box 12)	Automated algorithm	Map	Stratification map, support to visual interpretation, in few cases area estimation
Automated classification of satellite imagery using dense time-series analysis (see Box 13)	Automated algorithm	Map	Stratification map, support to visual interpretation, in few cases area estimation

Source: Authors' elaboration.

Sample-based area estimation: Expert visual interpretation of sample units has come to be seen as a robust approach for accurately assessing area of forest change from satellite imagery, including for detecting forest degradation, as long as high-resolution data are available (Gao *et al.*, 2020) The visual interpretation enables an easily implementable, sample-based assessment of satellite imagery to detect crown-cover reduction and disturbance, and in some cases, include indications of underlying processes, such as fire or logging (Gao *et al.*, 2020). In this visual approach, a human interpreter assigns a land cover and/or land cover change label to each sample unit based on characteristics identifiable in the satellite imagery. Multiple sources of imagery and other inputs can be used to help the interpreter label each sample.

Human interpretation allows for the contextualization of data over time and space, and does not require advanced computational algorithms (see Box 10); however, since the label of each sample is considered error-free, the interpretation must be done carefully as any classification errors are propagated in the results. The example from Uganda (see page 23) illustrates how the ability of photo interpreters to identify a logging event depends on the available imagery. Classification errors are often substantial, especially for those classes that are already hard to define, such as forest degradation. To minimize such potentially significant classification errors, many countries are introducing detailed quality management approaches, which are explicitly required by the leading carbon standards, ART-TREES, VCS-JNR and the FCPF Carbon Fund. Standard operating procedures routinely include detailed classification keys, provisions for interpreter training, and ongoing quality checks of interpretation results. In some contexts, it is becoming common practice to undertake multiple double-blind assessments of the same sample unit to boost robustness of interpretation and mitigate the effect of interpreter error (McRoberts *et al.*, 2018).

Automated algorithms: Automated processing of satellite imagery has been used for many years to convert raw spectral data into meaningful classifications. Such algorithms allow the efficient and systematic application of sophisticated computations over large geographic areas to facilitate map making and other large-area analyses. However, many traditional approaches to automated image classification and change detection, such as focusing on spectral response in satellite imagery from one time point or between two distinct dates, are often not effective at detecting and monitoring the more subtle characteristics of forest degradation (Gao *et al.*, 2020). Much work has been dedicated to developing more advanced and alternative approaches capable of classifying forest degradation. Some of the principal proposals include:

1. landscape fragmentation metrics as a proxy of forest degradation (see Box 11);
2. using granular scale of forest loss assessments to identify forest degradation (see Box 12); and
3. automated classification of satellite imagery using dense time-series analysis (see Box 13).

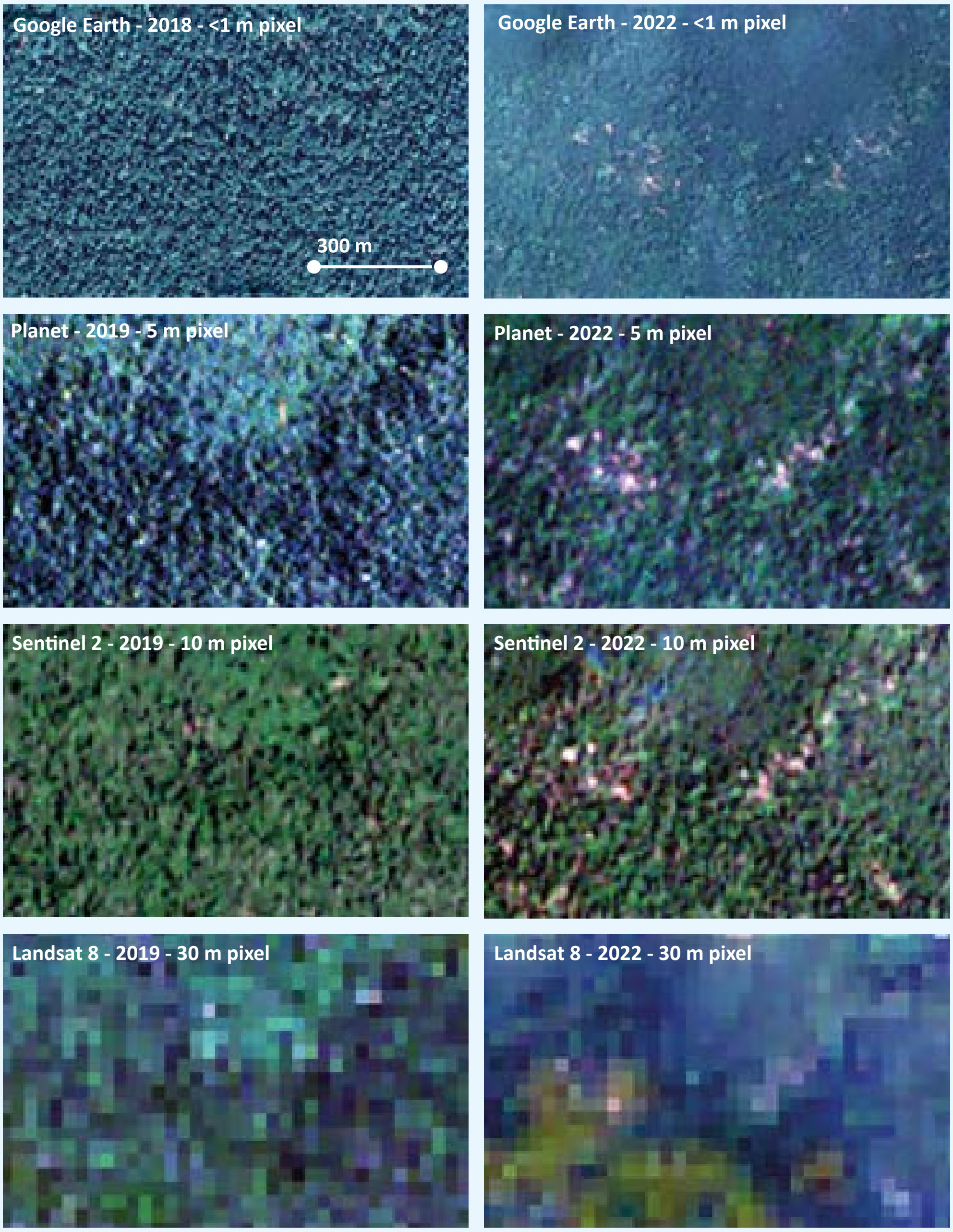
Maps alone are not suitable for estimating emissions. Some of the earlier reference level submissions to the UNFCCC used area statistics directly derived from forest degradation classes in a map (i.e. by pixel counts), but it is known that using the map alone does not provide robust and reliable estimates, especially where maps are created through post-classification (Sandker *et al.*, 2021). The resulting estimates are most likely biased estimates (either underestimated or overestimated) because map errors do not occur with the same likelihood across land cover classes. Because the estimates are biased, it is not possible to tell if the estimate is under-reporting or over-reporting emissions. Therefore, it is important to connect mapping efforts with some level of a sample-based approach.

Maps showing forest degradation areas are useful as stratifiers for distributing sample units and further visual interpretation. Since forest degradation is a relatively rare event as it tends to cover a low proportion of existing forest cover, many countries employ stratification techniques to guide intensive sampling in regions most likely impacted by degradation.

Box 10. Sample-based area estimation to measure forest degradation area, Uganda

A key determinant of achievable accuracy in visual image interpretation is the spatial resolution of available imagery. For a long time, Landsat imagery was the most widely used dataset for mapping forests; however, Landsat images have a spatial resolution of only 30 metres which is often insufficient to observe granular degradation events, depending on the minimum area unit applied in mapping. High-resolution images with a pixel size of around 5 metres from Planet Labs have recently been made freely available for most of the world's forests to enable better identification of forest features, including forest degradation. For instance, such improved data were rather useful during Uganda's FAO-supported data collection for visually assessing degradation events. Although the example below is more recent, Uganda used similar data to submit a forest reference level to the UNFCCC in 2018 and has also reported emission reductions for the years 2015–2017.[a]

Comparison of several types of imagery for the same area in Uganda's Mabira forest, before and after a logging event in 2021 at increasingly coarser resolutions



Notes: [a] For more information, see https://redd.unfccc.int/info-hub.html

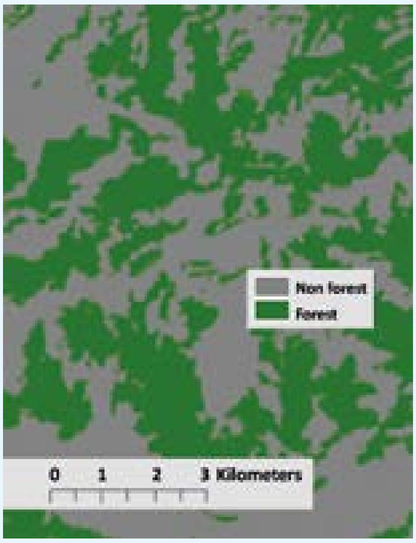
Source: Authors' elaboration.

Box 11. Characterization of forest degradation through landscape fragmentation metrics, Nepal

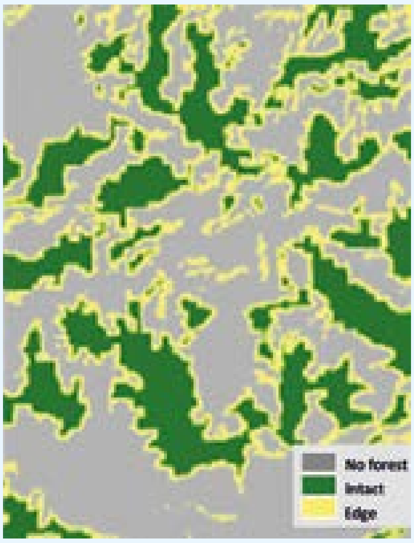
When submitting to the FCPF Carbon Fund,[a] Nepal estimated emissions from forest degradation based on forest degradation area measurements and biomass stock differences. To inform area measurements through sample-based area estimation, Nepal used an innovative stratification approach.[b]
For stratification, forest degradation was identified as the area changing its stratum between two timepoints, that is, from "*core*" or "*intact*" to "*forest edge*". The classification was undertaken as follows:

1. A binary forest / non-forest map was produced for the earlier time point.
2. Change data were used to infer the extent of the stable forest class for the second time point.
3. The morphological spatial pattern analysis was applied to both maps with a context analysis using a 5 m × 5 m window, identifying certain areas as "*forest edge*" and others as "*intact*".
4. Forest transitioning between the two timepoints from "*intact*" or "*core*" to "*forest edge*" were classified degraded.

Landscape structure change analysis undertaken in Nepal's emission reporting



Binary forest / non-forest map



Map of "*intact*" and "*edge*" forest

Source: Modified from Nepal's reporting to the FCPF Carbon Fund.

While the above discusses Nepal's original submission to the FCPF Carbon Fund, Nepal has since updated the mapping approach for the first reporting period of the FCPF Carbon Fund – and potentially for other results-based payments initiatives as well. In the new methodology, Nepal utilizes a combination of four different dense time-series analysis algorithms to derive a map covering several types of forest (change) strata, including forest degradation. The resulting map is then used as a stratifier for sample-based area estimation.

Notes: [a] For more information, see https://www.forestcarbonpartnership.org
[b] Shapiro, A.C., Aguilar-Amuchastegui, N., Hostert, P. & Bastin, J.-F. 2016. Using fragmentation to assess degradation of forest edges in Democratic Republic of the Congo. Carbon Balance and Management, 11(1): 11. https://doi.org/10.1186/s13021-016-0054-9

Source: Authors' elaboration.

Box 12. Automated detection of forest degradation through a granular scale of tree-cover loss assessments, Equatorial Guinea

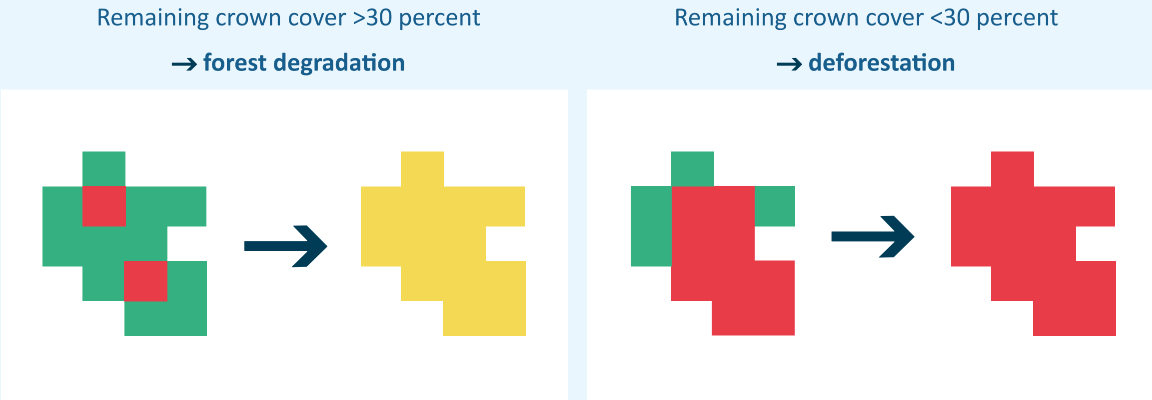
For compiling a reference level submission to the UNFCCC,[a] Equatorial Guinea analysed granular scale tree-cover losses using the Global Forest Change product:[b]

1. A Landsat image was segmented into polygons with a minimum size equalling the minimum area in the forest definition.

2. The polygons were overlaid with the Global Forest Change product.

3. Using a decision tree, polygons were classified as non-forest, intact forest, forest degradation and deforestation. Polygons were classified as forest degradation where some tree cover was lost, but sufficient tree cover remained to meet the forest definition.

Classification of polygons as deforestation or forest degradation according to granular scale forest loss



Source: Modified from Equatorial Guinea's reference level submission to the UNFCCC.

Notes: [a] For more information, see https://redd.unfccc.int/info-hub.html
[b] Hansen, M.C., Potapov, P.V., Moore, R., Hancher, M., Turubanova, S.A., Tyukavina, A., Thau, D. *et al.* 2013. High-Resolution Global Maps of 21st-Century Forest Cover Change. *Science*, 342(6160): 850-853. https://doi.org/10.1126/science.1244693

Source: Authors' elaboration.

Box 13. Automated detection of forest degradation through dense time-series analysis, the Central African Republic

In 2021–2022, FAO has provided support to several central African countries for mapping drivers of deforestation and forest degradation. Advanced remote sensing methods have been applied to detect the subtle differences over time that imagery displays after occurrence of forest degradation. Often, there has been only a short time window to detect disturbances through satellite imagery.

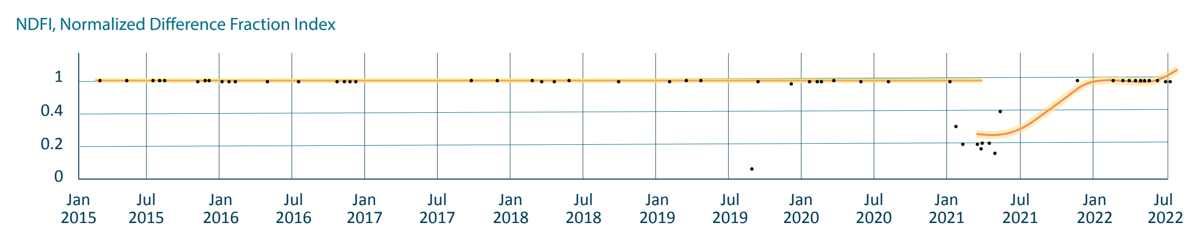
Figure A. Example of selective logging in high-resolution satellite imagery over evergreen tropical forest in the Central African Republic, southwest of Bania

Notes: A logging road was built in late-2020-early-2021 (A-C), which enabled selective logging to occur, peaking in May 2021 (D-E). By September 2021, the canopy had already closed again (F).

Time-series algorithms have been tailored to this challenge and aim to enable detection of short-term changes. The following are examples of algorithms that leverage improved data availability and processing power, and enhance classification performance: Breaks For Additive Seasonal and Trend (BFAST),[a] Continuous Change Detection and Classification (CCDC),[b] and LandTrendR.[c, d] Some of them operate on each single cloud-free pixel, such as BFAST and CCDC, while others use yearly aggregates of the data, such as LandTrendR. These algorithms are usually run on synthetic indices (such as the Normalized Difference Vegetation Index [NDVI] or the Normalized Difference Fraction Index [NDFI]). FAO's SEPAL platform enables running BFAST, CCDC and others, with further algorithms to be added soon.

A CCDC trend model is fitted to the NDFI time-series associated with selective logging. The historical signal is largely stable: the stable trend breaks in the first quarter of 2021, upon the logging event; by the end of 2021, NDFI values returned to the pre-disturbance level.

Figure B. Time-series associated with selective logging in Figure A.

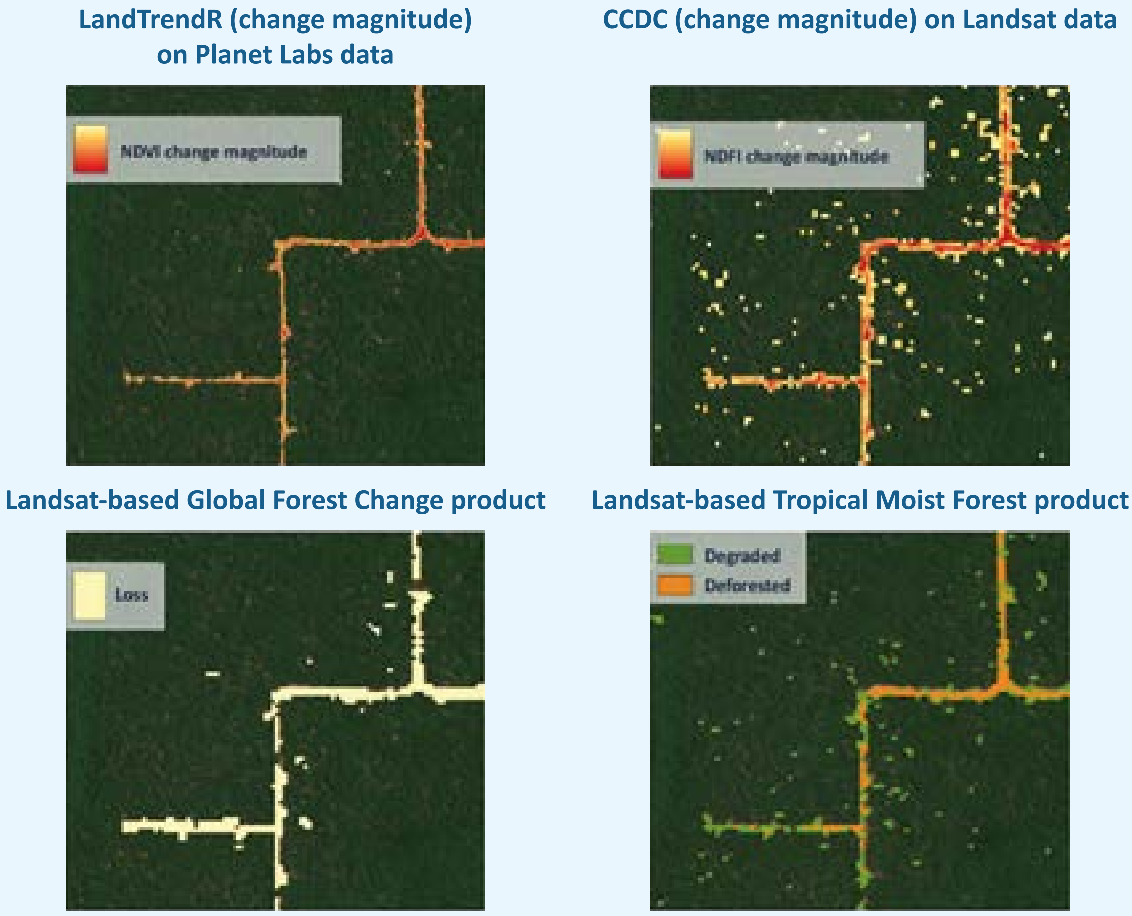


Notes: White dots represent the actual NDFI observations; the yellow line represents a fitted harmonic model from the CCDC algorithm with its associated root-mean squared error in the semi-opaque bands.

Different combinations of algorithms and underlying satellite data sources need to be compared to identify the most powerful algorithms. In this example, both LandTrendR and CCDC performed well; however, the University of Maryland's Global Forest Change product[e] and the Joint Research Centre's Tropical Moist Forest product[f] delivered convincing results.

Source: Authors' elaboration.

Figure C. Results from classification using different combinations of time-series algorithms and underlying data products on the example case shown in Figure A.



Notes: [a] Verbesselt, J., Hyndman, R., Zeileis, A. & Culvenor, D. 2010. Phenological change detection while accounting for abrupt and gradual trends in satellite image time series. *Remote Sensing of Environment*, 114(12): 2970-2980. https://doi.org/10.1016/j.rse.2010.08.003

[b] Zhu, Z. & Woodcock, C.E. 2014. Continuous change detection and classification of land cover using all available Landsat data. *Remote Sensing of Environment*, 144: 152-171. https://doi.org/10.1016/j.rse.2014.01.011

[c] Cohen, W.B., Yang, Z. & Kennedy, R. 2010. Detecting trends in forest disturbance and recovery using yearly Landsat time series: 2. TimeSync — Tools for calibration and validation. *Remote Sensing of Environment*, 114(12): 2911-2924. https://doi.org/10.1016/j.rse.2010.07.010

[d] Kennedy, R.E., Yang, Z. & Cohen, W.B. 2010. Detecting trends in forest disturbance and recovery using yearly Landsat time series: 1. LandTrendr — Temporal segmentation algorithms. *Remote Sensing of Environment*, 114(12): 2897-2910. https://doi.org/10.1016/j.rse.2010.07.008

[e] Hansen, M.C., Potapov, P.V., Moore, R., Hancher, M., Turubanova, S.A., Tyukavina, A., Thau, D. *et al.* 2013. High-Resolution Global Maps of 21st-Century Forest Cover Change. Science, 342(6160): 850-853. https://doi.org/10.1126/science.1244693

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Source: Authors' elaboration.

5. Estimating emissions and removals from forest degradation in the field

Countries have used several types of field data when estimating emissions and removals from forest degradation. The datasets range from national-scale inventories down to measurement taken for growth trials in no more than a handful of locations. Both estimates of carbon stocks and carbon stock changes are of interest, depending on the estimation approaches (see Table 4).

Table 4. Several types of field data relevant for estimating carbon stock changes associated with forest degradation

Description	Approach	Output	Objective
Measurement of carbon stock	Sampling through (usually temporary) field plots, including through national forest inventories	Estimate of carbon stock	Estimation of emission factors for forest degradation events when using *Areas and biomass stocks*, as per Section 2
Estimation of regrowth after degradation events	Measurement through permanent field plots for selected growth trials	Estimate of carbon stock changes	Estimation of removal factors for regrowth after degradation events when using *Areas and biomass stocks* or *Wood extraction versus regrowth*, as per Section 2
Estimation of biomass loss associated with logging	Collection of several kinds of datasets on logging impacts for selected case examples	Estimate of collateral damages associated with logging	Estimation of emission factors for logging events (also known as logging damage factor), reflecting both timber extracted and collateral damages when using *Wood extraction versus regrowth*, as per Section 2
Measurement of aggregate carbon stock changes	Sampling through (ideally) permanent field plots, including through national forest inventories	Estimate of carbon stock changes	Estimation of carbon stock changes using *Direct measurement of changes in biomass stocks*, as per Section 2

Source: Authors' elaboration.

Measurement of carbon stock: Emission factors for deforestation and forest degradation are often based on estimates of forest carbon stocks. When countries use the approach, *Areas and biomass stocks* (see Section 2), expected emissions per area unit are routinely approximated as the difference in carbon stock between undegraded forest and degraded forest (see Section 3.2 for more information on how forests can be stratified to separate undegraded and degraded forest, as well as the time periods to be considered here). Carbon stock estimates are, most commonly, derived from sampling through field plots, such as through national forest inventories.

Estimation of regrowth after degradation events: Since forest degradation events cause not only a drop in forest biomass, but also the subsequent regrowth as forest recovers, estimates of regrowth are needed when using *Areas and biomass stocks* or *Wood extraction versus regrowth* (see Section 2). With these methods, removal factors are typically derived from (representative) growth trials (for more information on tracking regrowth for entire countries, see **Measurement of aggregate carbon stock changes for a whole country**). The variation among estimates is considerable, but largely supports the view that regrowth could significantly accelerate post-logging.[14] There are two approaches to measure regrowth: the use of permanent sample plots with periodic remeasurements or the analysis of tree ring data (see Box 14). Periodic remeasurements need to be undertaken over long time frames, but analysis of tree ring data can yield results from one-off measurements. Since both approaches are resource intensive, countries often decide to use results from scientific literature rather than carrying out measurements directly.

Estimation of biomass loss associated with logging: Several countries have opted to estimate emissions associated with logging and the make of *Wood extraction versus regrowth*. This method relies on estimating emissions per unit of wood extraction. Emissions relate not only to the volume of timber extracted, but estimates need to factor in the biomass of harvested trees, as well as collateral logging damage and damage from skidding trees. Measuring these various types of damages requires intensive fieldwork and can only be undertaken for case examples, but not in a systematic fashion (see Box 15).

Measurement of aggregate carbon stock changes for a whole country: When countries use the method *Direct measurement of changes* in biomass stocks, this involves tracking carbon-stock changes through a field inventory of permanent sample plots with periodic remeasurement, such as part of a national forest inventory. It is essential that permanent rather than temporary sample plots be used. Since this enables revisiting the same trees periodically and observing change directly, uncertainties could be reasonable, while uncertainties could be too high when inferring stock change from stock measurements of temporary sample plots (see Box 16).

Box 14. Tree ring method in Bhutan

Tree growth and associated removals, including after forest degradation events, can be estimated using one-off measurements (i.e. temporary sample plots) through the tree ring method. Bhutan collected such data in 2014 in the context of their national forest inventory. For every inventory plot, trees with median diameter were selected and two drill cores were extracted at breast height. The width of tree rings visible in the cores provided an indication of diameter growth patterns over the years. The combination with an allometric model enabled estimating annual growth in volume and biomass across the country's temperate forests.[a]

The tree ring method has some limitations. Tree ring analysis relies heavily on forests presenting strong seasonality, where tree rings are clearly visible, which is mainly the case in temperate and boreal environments. Associated uncertainties are significant since only few trees can be examined and there is a risk that these could be unrepresentative. Finally, tree mortality cannot be examined. Despite such limitations, the approach should still be preferable to using generic literature values.

Notes: [a] Tenzin, J., Tenzin, K. & Hasenauer, H. 2017. Individual tree basal area increment models for broadleaved forests in Bhutan. *Forestry*: 90(3): 367-380. https://doi.org/10.1093/forestry/cpw065

Source: Authors' elaboration.

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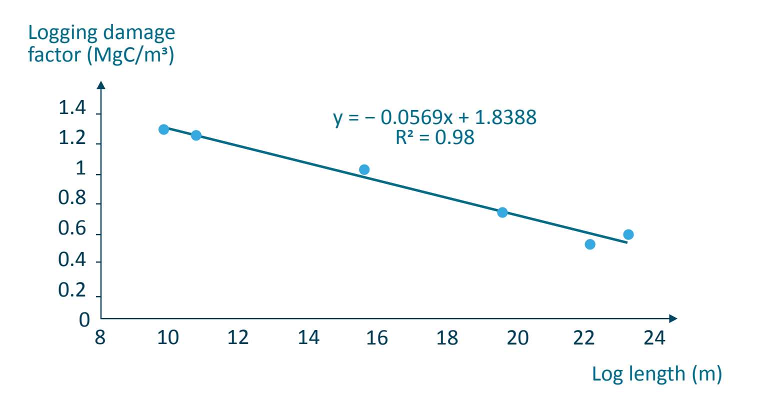
[14] Studies undertaken for locations in Indonesia, Brazil, Mexico and Suriname indicated recovery rates of 0.5–4.6 tC/ha/yr (Berry *et al.*, 2010; Butarbutar *et al.*, 2019; Lobo *et al.*, 2007; Mazzei *et al.*, 2010; Poorter *et al.*, 2016; Roopsind *et al.*, 2017; Vidal *et al.*, 2016; West *et al.*, 2014)

Box 15. Logging damage factor in Guyana

When estimating emissions from selective logging, Guyana estimated emission factors that related the total biomass damaged to the volume of timber extracted, based on a method described in scientific literature.[a] Accordingly, emission factors for selective logging are developed in relation to the volume of timber extracted, factoring in the biomass of harvested trees, as well as collateral logging damage and damage from skidding trees. These various types of damages were measured through detailed inventories of case studies in several countries around the world. Collectively, the biomass loss amounts to about three times the biomass in harvested volume.

Correlation between mean log length and logging damage factor in six case studies



Source: From Pearson *et al.*, 2014, referenced in the ART-TREES registration document.

Notes: [a] Pearson, T.R.H., Brown, S. & Casarim, F.M. 2014. Carbon emissions from tropical forest degradation caused by logging. *Environmental Research Letters*, 9(3): 034017. https://doi.org/10.1088/1748-9326/9/3/034017

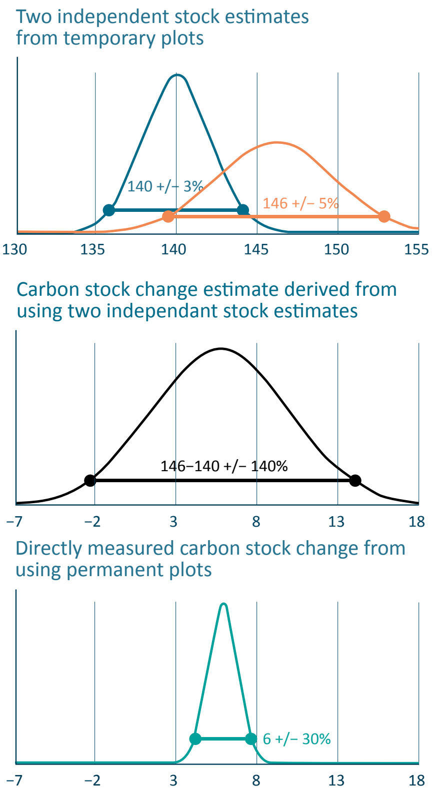
Source: Authors' elaboration.

Box 16. Uncertainties when using temporary vs permanent sample units for measuring stock change

When estimating carbon stock changes, whether from losses or regrowth, is the objective, then sample plots could be temporary or permanent. For temporary plots, the measurements are taken for each cycle independently. The errors are also independent of each other, and the standard error propagation rules apply. Conversely, when using permanent plots, change can be observed directly, which translates into much smaller uncertainties.[a]

For example, two independent stock estimates from temporary plots may result in estimates and uncertainties of 140 tC/ha +/− 3% and 146 tC/ha +/− 5%. The estimate of stock change amounts to 6 tC/ha +/− 140%. However, using permanent sample plot design may have resulted in an estimate that is much less uncertain, such as 6 tC/ha +/− 30%.

Large and smaller uncertainties in estimating biomass changes from independent field measurements of biomass stocks and from directly measuring change



Albeit performance of estimation must be expected to be superior when using permanent sample units, countries have mostly used temporary plot designs in the tropics. Technical and logistical challenges in revisiting permanent sample units years later have been found to be significant in many countries, especially in the remote environments that are common in tropical rainforests.[b]

Notes: [a] Räty, M. & Kangas, A.S. 2019. Effect of permanent plots on the relative efficiency of spatially balanced sampling in a national forest inventory. *Annals of Forest Science*, 76(1): 20. https://doi.org/10.1007/s13595-019-0802-6

[b] Nesha, K., Herold, M., De Sy, V., de Bruin, S., Araza, A., Málaga, N., Gamarra, J.G.P. *et al.* 2022. Exploring characteristics of national forest inventories for integration with global space-based forest biomass data. *Science of The Total Environment*, 850: 157788. https://doi.org/10.1016/j.scitotenv.2022.157788

Source: Authors' elaboration.

6. Choosing the estimation approach

The choice of the approach for estimating forest degradation will depend on the requirements of applicable carbon standards, as well as on the country context, that is, the available datasets and the characteristics of prevailing forests and degradation processes.

6.1. FOREST DEGRADATION AND CARBON STANDARDS

Forest degradation is a key source of emissions in most countries (see Section 1.2). Because of this, many countries include forest degradation in their international reporting, notably under the UNFCCC. Where generating carbon credits under a reputable carbon standard is an objective, including forest degradation is a mandatory requirement in most cases. Although there is some flexibility when reporting under the UNFCCC and the GCF, its official financing mechanism – carbon finance initiatives that also issue carbon credits, ART-TREES, the VCS-JNR and the FCPF Carbon Fund – will usually require reporting on forest degradation (see Table 5).

Table 5. Requirements on the REDD+ activities to be covered in leading carbon standards for jurisdictional REDD+

<table>
<tr><th></th><th colspan="4">Carbon standards</th></tr>
<tr><th></th><th>ART-TREES</th><th>VCS-JNR</th><th>FCPF Carbon Fund</th><th>GCF RBP pilot programme</th></tr>
<tr><td>Emissions from deforestation</td><td>Required</td><td>Required</td><td>Required</td><td rowspan="4">Same scope as UNFCCC submission (can be excluded if insignificant or if data are lacking)</td></tr>
<tr><td>Emissions from forest degradation</td><td>Required (can be excluded if conservative or insignificant)</td><td>Required (can be excluded if insignificant)</td><td>Required (can be excluded if insignificant)</td></tr>
<tr><td>Removals from standing forests</td><td>Excluded</td><td>Excluded</td><td>Optional</td></tr>
<tr><td>Removals from new forests</td><td>Optional (only if emissions have been reduced)</td><td>Excluded</td><td>Optional</td></tr>
</table>

Source: Authors' elaboration.

In all these contexts, forest degradation can be excluded from reporting if the resulting emissions are not significant;[15] however, as clarified above, in many developing countries, forest degradation emissions are significant. Forest degradation emissions were less than 10 percent of total emissions in the reference level for only a few of the countries that submitted reference levels to the UNFCCC (see Section 1.2).

Carbon standards also include specific methodological guidance, and not all estimation approaches are eligible under all standards (see Table 6). The *Areas and biomass stocks approach* can be undertaken under all

[15] Significance is defined differently in these different contexts. ART-TREES indicates degradation emissions can be excluded if they are less than 10 percent of deforestation emissions, while the FCPF Methodological Framework and the VCS-JNR indicate degradation emissions can be omitted if they are less than 10 percent of total forest-related emissions in the accounting area. The requirements of the GCF RBP pilot programme do not define significance.

standards, although there are some restrictions regarding the allowable methods for estimating degradation areas and regarding the use of long-term averages and annual regrowth tracking. *The Wood extraction versus regrowth* approach is eligible under ART-TREES and the FCPF Carbon Fund, as well as for the GCF RBP pilot programme, but not under VCS-JNR. *Direct measurement of changes in biomass stocks* cannot be undertaken under ART-TREES or VCS-JNR, but it is eligible under the FCPF Carbon Fund and the GCF RBP pilot programme.

Table 6. Eligibility of different estimation approaches under the carbon standards

<table>
<tr><th></th><th>ART-TREES</th><th>VCS-JNR</th><th>FCPF CF</th><th>GCF RBP pilot programme</th></tr>
<tr><td>Areas and biomass stocks</td><td>Eligible
Area measurements to be undertaken by sample-based area estimation; emission factors usually reflect long-term average postdegradation carbon stock</td><td>Eligible
Area measurements to be undertaken by sample-based area estimation; emission factors must reflect long-term average postdegradation carbon stock</td><td rowspan="3">Eligible</td><td rowspan="3">Eligible
As long as included in the UNFCCC submissions</td></tr>
<tr><td>Wood extraction versus regrowth</td><td>Eligible</td><td>Not eligible</td></tr>
<tr><td>Direct measurement of changes in biomass stocks</td><td>Not eligible</td><td>Not eligible</td></tr>
</table>

Source: Authors' elaboration.

Moreover, countries will need to closely consider requirements in carbon standards on the allowable uncertainty of emission reduction estimates. As pointed out in the sections on the estimation approaches (see Section 3.2 and Section 5), uncertainties could attain high levels, depending on the estimation approaches and the datasets available. Since high uncertainties entail a risk of overestimating emission reductions, the carbon standards include discounts. For example, ART-TREES, VCS-JNR and the FCPF Carbon Fund all require discounts, which grow with the amount of uncertainty and could amount to a large portion of emission reductions. Under the VCS-JNR, programmes where uncertainties exceed 100 percent are not eligible for crediting at all. Such guidance in carbon standards translates into an incentive for countries to select the most suitable estimation approaches and strengthen datasets to reduce uncertainties, when practicable.

A key requirement in carbon standards is that a verification of reported emission reductions be undertaken (Neeff and Lee, 2018). An external third-party, usually a duly accredited auditing firm, will check on the emission reduction claims and issue a statement providing assurance on its correctness, so that it can become a basis for issuance of carbon credits. An important step in this process is the quality control of data reported. Several sections of this report point out how challenging it is to measure and report on emissions from forest degradation emissions. The verification process will therefore be particularly important – and potentially incisive – for any reported emission reductions from forest degradation. To date, little knowledge has been attained on this because very few countries with mitigation programmes have yet undergone such verifications (see Table 7).

Table 7. Progress towards verification under leading carbon standards

	ART-TREES	VCS-JNR	FCPF Carbon Fund	GCF RBP pilot programme
Programmes identified	15 concept notes submitted and included in the registry	1 programme included in the registry	47 countries have joined the FCPF	56 countries have reported reference levels to the UNFCCC, 33 of which include forest degradation
Programmes with detailed submissions	2 registration documents submitted	Not yet	18 countries have submitted emission reductions programme documents (ER-PDs), 17 of which include forest degradation	8 countries that have submitted funding proposals to the GCF RBP pilot programme
Programmes verified for emission reductions	No verifications concluded yet	Not yet	3 verifications concluded	Verification not foreseen

Notes: Updated October 2022.

Source: Authors' elaboration.

6.2. FOREST DEGRADATION AND COUNTRY CONTEXT

The choice of method will depend on technical aspects: the type of forest degradation (i.e. what was driving it), the characteristics of prevailing forest types (variability over time and space), and the availability of data, such as high-resolution satellite imagery or wood use statistics (see Table 8).

Table 8. Technical limitations and opportunities for the approaches to estimating emissions from forest degradation

Estimation approach	Challenges…	Could work if these data are available…	Could work for these types of forest and types of forest degradation…
Areas and biomass stocks	• Hard to correlate biomass stocks loss against what is observable in satellite imagery (e.g. crown cover changes) • Difficult to define time frame for considering postdegradation regrowth	• Field measurements of biomass stock, including for degraded forest • High-quality Earth observation data where degradation events are clearly visible in imagery	• Where there is less seasonal variability and where forests are less variable depending on micro conditions • Where a typical "*degraded forest*" with a biomass density can be established
Wood extraction versus regrowth	• Quality of logging statistics could be variable • Postdegradation regrowth hard to establish • Need to establish area for logging • Harvesting damages could vary greatly	• High-quality logging statistics with only limited occurrence of informal wood use • High-quality information on post-degradation regrowth • Information on harvesting approaches and associated damages	• Where logging a key source of emissions and removals • Where informal wood use is limited • Where logging practices are sufficiently uniform to estimate average impact • Where typical regrowth dynamics can be established
Direct measurement of changes in biomass stocks	• Estimates only available for long time intervals • Uncertainties too high with temporary sample plots • Revisiting permanent sample plots is hard • May end up measuring net removals rather than net emissions	• Permanent sample plots being measured periodically, which is highly resource intensive	• Could work for most types of forests

Source: Authors' elaboration.

Areas and biomass stocks works well wherever a robust correlation can be established between detected degradation when measuring areas and the concomitant drop in biomass. This requirement may not always hold. Detecting certain types of forest degradation in satellite imagery can be very hard (for instance, wood fuel collection may be hardly visible), especially when using certain datasets (for example, medium resolution imagery will often not suffice or image availability may be insufficient given persistent cloud cover), or depending on the type of forests (for instance, seasonal variability may introduce too much noise).

Wood extraction versus regrowth has demanding data requirements on harvested volumes, forests increments and patterns of wood use. Determinative will be the coverage and quality of official logging statistics, which can vary greatly across countries; for example, in countries with high amounts of informal wood use (whether for timber or fuelwood), official statistics will be underestimates. Moreover, information is needed on damages inflicted upon forests during harvesting operations, which could be hard to quantify because logging damages greatly depend on the approach to planning the logging operation, the skill of the forest operator, and their commitment to reducing logging impacts. Finally, an important limitation will often be the availability of high-quality information on increments. Few countries have robust information on biomass gains available within areas that undergo wood use.

Direct measurement of changes in biomass stocks requires that countries have access to high-quality national forest inventories, ideally with permanent sample plots, which are only available in some countries. Permanent sample plots would allow measuring change directly, while the comparison of averages across multiple forest inventory cycles with temporary sample plots will yield estimates with uncertainties too high to draw any robust conclusions. Even where it can be implemented, the approach is also limited because it only delivers results according to the periodicity of field data collection, which could be too infrequent for most international reporting processes.

7. Conclusions

Estimating emissions and removals from forest degradation is important, yet challenging, for many countries. Where forest degradation is a major source of emissions, governments wish to cover it when reporting on their mitigation efforts (see Section 1.2); however, estimating emissions from forest degradation is difficult.

There are three main challenges to accurately estimating emissions from degradation (see Section 1.3):

1. defining forest degradation and setting the scope for estimating carbon stock changes;
2. detecting and monitoring degradation using Earth observation data; and
3. estimating associated emissions from field observation results.

This paper provides an overview of the methodological options available to countries to address these challenges.

There is much country experience available on estimating carbon stock changes from forest degradation and methodological options are emerging. Dozens of countries have reported internationally on emissions from forest degradation (see Section 2). Most of the approaches can be grouped into three basic methodological options (see Section 2), although there remains much variability within those basic options regarding the definitions applied and the datasets used (see Section 3, Section 4 and Section 5).

How well methodological options could work, depends on the country context (see Section 6.2). If there is a desire or a need to track emissions from specific drivers, this will dictate the estimation approach. Some estimation approaches can only be used where certain high-quality datasets are available (for example, high-quality logging statistics or forest inventory with permanent sample plots). Remote sensing-based approaches struggle in forests that are highly variable – either seasonally or across the landscape – and persistent cloud cover and certain types of terrain can also cause challenges.

The choice of the approach for estimating forest degradation will also depend on the requirements of applicable carbon standards – next to the country context and what methods work well (see Section 6.1). Leading carbon standards and results-based payments schemes include detailed requirements on the treatment of forest degradation that interested countries follow.

There remain unresolved questions on basic reporting aspects of forest degradation emissions. For example, there is much variability among carbon standards for jurisdictional mitigation programmes on the eligible basic methods, highlighting less than full consensus on what works well (see Section 6.1). Although the *Areas and biomass stocks* approach can be used under all the leading carbon standards, the *Wood extraction versus regrowth* approach cannot be used under VCS-JNR, and neither ART-TREES nor VCS-JNR allow the *Direct measurement of changes in biomass stocks* approach. Country cases also highlight that there is no full consensus on key methodological questions, such as regarding the treatment of regrowth after the degradation event. Some countries neglect postdegradation regrowth (see Box 4); others account for it annually (see Box 8); others apply long-term averages (see Box 9).

There could be contexts where robust measurements of forest degradation emissions are very hard to come by. For example, detecting forest degradation in satellite imagery works best with high-resolution images (see Box 10), but for older dates only medium resolution data might be available (i.e. before the 2015 onset of freely available images from Planet Labs). Because of this, quality management in visual interpretation is both a top priority and a field of ongoing learning (see Section 3.2). For instance, clearly defining forest degradation could be hard in forests with much natural and seasonal variability (see Section 1.3), making measurement protocols unreliable. Countries may nonetheless wish to report on forest degradation emissions – it is mandatory under most carbon standards (see Section 6.2). At the same time, it is still unclear whether the verifications, a key step in carbon credit programmes, can effectively guarantee high-quality emission reduction estimates. So far, only a handful of such verifications could be completed of mitigation programmes targeting forest degradation (see Section 6.1). With challenges in estimating forest degradation emissions, countries reporting nonetheless to meet standards' requirements, and the fact that there have only been initial verification experiences to date, there is a risk that some of the forest degradation reports could be less than fully robust.

Recent and ongoing investments into data and analysis methods have helped improve forest degradation estimation, but further methodological work and continued effort will be needed. For example, detection of forest degradation in satellite images is a field of active research where advanced algorithms are being developed and applied to vast datasets (see Box 13). The many countries that have already reported on forest degradation have generated invaluable lessons learned on applying methods at a country level (see Section 2). Nonetheless, there are opportunities for further learning.

The following steps could lead to the improvement of measuring emissions from forest degradation:

1. Continue transparent sharing of information among countries and organizations involved in emission estimation and reporting, estimation approaches, and underlying datasets and methods, including the use of open-source software.

2. Continue improving availability of high-resolution imagery and sustaining the availability of such imagery in time, since it could enable identifying forest degradation more reliably.

3. Continue testing advanced remote-sensing approaches (high-density time-series analysis and others) to detect forest degradation – including the use of advanced datasets, such as utilizing laser or radar sensors.

4. Evaluate effectiveness of quality management in measuring emission reductions (notably from initial verifications and ongoing country efforts towards quality assurance in data collection) and insert lessons learned into measurement and reporting protocols, carbon standards technical guidance, and verification protocols.

5. Where possible, review technical guidance for emissions reporting, including carbon standards and donor requirements, to ensure that guidance responds to what is measurable rather than what is desirable from a policy perspective.

6. Work towards a consensus on treatment of postdegradation regrowth (whether or not it must be accounted for, whether to estimate annual or expected carbon stock changes, what the right time frames should be, and how this should be implemented in carbon standards).

7. Collect more and better information on dynamics of forest biomass emissions and removals over time, developing robust datasets on postdegradation regrowth patterns and applicable management regimes, which would improve the ability to separate the initial biomass loss during a degradation event from the gradual regrowth during the following years.

8. In some countries, strengthen datasets on forest degradation drivers, both regarding their occurrence, such as mapping logging, fire and others through Earth observation, and develop robust datasets on logging damages associated with harvests, on informal wood use.

9. Test national forest inventories with permanent sample plots to quantify stock changes in forests, and therefore emissions, from forest degradation.

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