



SOURCEBOOK



Reducing Greenhouse Gas Emissions from Deforestation and Degradation in Developing Countries: A Sourcebook of Methods and Procedures for Monitoring, Measuring and Reporting

GOFC-GOLD 

REDUCING GREENHOUSE GAS EMISSIONS FROM DEFORESTATION AND DEGRADATION IN DEVELOPING COUNTRIES: A SOURCEBOOK OF METHODS AND PROCEDURES FOR MONITORING, MEASURING AND REPORTING

Background and Rationale for the Sourcebook

This sourcebook provides a consensus perspective from the global community of earth observation and carbon experts on methodological issues relating to quantifying the green house gas (GHG) impacts of implementing activities to reduce emissions from deforestation and degradation in developing countries (REDD). The UNFCCC negotiations and related country submissions on REDD in 2005-2007 have advocated that methodologies and tools become available for estimating emissions from deforestation with an acceptable level of certainty. Based on the current status of negotiations and UNFCCC approved methodologies, this sourcebook aims to provide additional explanation, clarification, and methodologies to support REDD early actions and readiness mechanisms for building national REDD monitoring systems. It emphasizes the role of satellite remote sensing as an important tool for monitoring changes in forest cover, and provides clarification on applying the IPCC Guidelines for reporting changes in forest carbon stocks at the national level.

The sourcebook is the outcome of an ad-hoc REDD working group of "Global Observation of Forest and Land Cover Dynamics" (GOF-C-GOLD, www.fao.org/gtos/gofc-gold/), a technical panel of the Global Terrestrial Observing System (GTOS). The working group has been active since the initiation of the UNFCCC REDD process in 2005, has organized REDD expert workshops, and has contributed to related UNFCCC/SBSTA side events and GTOS submissions. GOF-C-GOLD provides an independent expert platform for international cooperation and communication to formulate scientific consensus and provide technical input to the discussions and for implementation activities. A number of international experts in remote sensing and carbon measurement and accounting have contributed to the development of this sourcebook.

With political discussions and negotiations ongoing, the current document provides the starting point for defining an appropriate monitoring framework considering current technical capabilities to measure gross carbon emission from changes in forest cover by deforestation and degradation on the national level. This sourcebook is a living document and further methods and technical details can be specified and added with evolving political negotiations and decisions. Respective communities are invited to provide comments and feedback to evolve a more detailed and refined technical-guidelines document in the future. We acknowledge the following people for the comments which were made on the first version distributed in December 2007 in Bali: Margaret Skutsch, Sharon Gomez, David Shoch, Bill Stanley, Steven De Gryze, Albert Ackhurst and Doug Muchoney, and the following people for the comments which were made on the second version distributed in June 2008: Jeffrey Himel, Sandro Federici (Section 1. Introduction)

...

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50

51 This publication is the result of a joint voluntary effort from a number of experts from
52 different institutions (that they may not necessarily represent). It is still an evolving
53 document. The experts who contributed to the present version are listed under the
54 chapter(s) to which they contributed.

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124
125
126
127
128
129
130
131
132
133
134
135
136
137
138
139
140
141
142
143

Table of Contents

1	INTRODUCTION	1-6
1.1	PURPOSE AND SCOPE OF THE SOURCEBOOK	1-6
1.2	ISSUES AND CHALLENGES	1-7
1.2.1	<i>LULUCF in the UNFCCC and Kyoto Protocol.....</i>	<i>1-7</i>
1.2.2	<i>Definition of Forests, Deforestation and Degradation</i>	<i>1-8</i>
1.2.3	<i>General Method for Estimating CO₂ Emissions</i>	<i>1-11</i>
1.2.4	<i>Reference Emissions Levels and Benchmark Forest Area Map.....</i>	<i>1-13</i>
1.2.5	<i>Roadmap for the Sourcebook.....</i>	<i>1-14</i>
2	METHODOLOGICAL SECTION	2-15
2.1	GUIDANCE ON MONITORING OF CHANGES IN FOREST AREA.....	2-15
2.1.1	<i>Scope of chapter</i>	<i>2-15</i>
2.1.2	<i>Monitoring of changes of forest areas - deforestation and reforestation</i>	<i>2-16</i>
2.1.3	<i>Monitoring of forest area changes within forests - forest land remaining forest land</i>	<i>2-26</i>
2.1.4	<i>Key references for Section 2.1</i>	<i>2-39</i>
2.2	ESTIMATION OF ABOVE GROUND CARBON STOCKS	2-40
2.2.1	<i>Scope of chapter</i>	<i>2-40</i>
2.2.2	<i>Overview of carbon stocks, and issues related to C stocks</i>	<i>2-40</i>
2.2.3	<i>Which Tier should be used?.....</i>	<i>2-42</i>
2.2.4	<i>Stratification by Carbon Stocks</i>	<i>2-46</i>
2.2.5	<i>Estimation of Carbon Stocks of Forests Undergoing Change</i>	<i>2-51</i>
2.3	ESTIMATION OF SOIL CARBON STOCKS	2-63
2.3.1	<i>Scope of chapter</i>	<i>2-63</i>
2.3.2	<i>Explanation of IPCC Tiers for soil carbon estimates</i>	<i>2-63</i>
2.3.3	<i>When and how to generate a good Tier 2 analysis for soil carbon.....</i>	<i>2-64</i>
2.3.4	<i>Emissions as a result of land use change in peat swamp forests</i>	<i>2-68</i>
2.4	METHODS FOR ESTIMATING CO ₂ EMISSIONS FROM DEFORESTATION AND FOREST DEGRADATION	2-72
2.4.1	<i>Scope of this Chapter.....</i>	<i>2-72</i>
2.4.2	<i>Linkage to 2006 IPCC Guidelines</i>	<i>2-73</i>
2.4.3	<i>Organization of this Chapter</i>	<i>2-73</i>
2.4.4	<i>Fundamental Carbon Estimating Issues</i>	<i>2-74</i>
2.4.5	<i>Estimation of Emissions from Deforestation</i>	<i>2-76</i>
2.4.6	<i>Estimation of Emissions from Forest Degradation.....</i>	<i>2-79</i>
2.5	METHODS FOR ESTIMATING GHG'S EMISSIONS FROM BIOMASS BURNING	2-81
2.5.1	<i>Scope of chapter</i>	<i>2-81</i>
2.5.2	<i>Introduction</i>	<i>2-81</i>
2.5.3	<i>IPCC guidelines for estimating fire-related emission.....</i>	<i>2-84</i>
2.5.4	<i>Mapping fire from space.....</i>	<i>2-85</i>
2.5.5	<i>Using existing products</i>	<i>2-89</i>
2.5.6	<i>Key references for Section 2.5</i>	<i>2-91</i>
2.6	UNCERTAINTIES	2-92
2.6.1	<i>Scope of chapter</i>	<i>2-92</i>
2.6.2	<i>General concepts</i>	<i>2-92</i>
2.6.3	<i>Quantification of uncertainties</i>	<i>2-94</i>
2.6.4	<i>Key References for Section 2.6</i>	<i>2-104</i>
2.7	STATUS OF EVOLVING TECHNOLOGIES	2-106
2.7.1	<i>Scope of Chapter.....</i>	<i>2-106</i>
2.7.2	<i>Role of LIDAR observations</i>	<i>2-107</i>
2.7.3	<i>Forest monitoring using Synthetic Aperture Radar (SAR) observations</i>	<i>2-111</i>
2.7.4	<i>Integration of satellite and in situ data for biomass mapping</i>	<i>2-115</i>
2.7.5	<i>Targeted airborne surveys to support carbon stock estimations – a case study.....</i>	<i>2-117</i>
2.7.6	<i>Modeling and forecasting forest-cover change.....</i>	<i>2-119</i>
2.7.7	<i>Summary and recommendations.....</i>	<i>2-120</i>
2.7.8	<i>Key references for Section 2.7</i>	<i>2-122</i>

145	3 PRACTICAL EXAMPLES FOR DATA COLLECTION.....	3-124
146	3.1 OVERVIEW OF METHODS USED BY ANNEX-1 COUNTRIES FOR NATIONAL LULUCF	
147	INVENTORIES.....	3-124
148	3.1.1 <i>Scope of chapter</i>	3-124
149	3.1.2 <i>Methods for estimating forest area changes</i>	3-125
150	3.1.3 <i>Methods for estimating carbon stock changes</i>	3-127
151	3.1.4 <i>National carbon budget models</i>	3-128
152	3.1.5 <i>Estimation of uncertainties</i>	3-132
153	3.1.6 <i>Key References for section 3.1</i>	3-133
154	3.2 OVERVIEW OF THE EXISTING FOREST AREA CHANGES MONITORING SYSTEMS.....	3-134
155	3.2.1 <i>Scope of chapter</i>	3-134
156	3.2.2 <i>National Case Studies</i>	3-134
157	3.2.3 <i>Key references for Section 3.2</i>	3-139
158	3.3 NATIONAL FOREST INVENTORY: INDIA'S CASE STUDY.....	3-140
159	3.3.1 <i>Scope of chapter</i>	3-140
160	3.3.2 <i>Introduction on forest inventories in tropical countries</i>	3-140
161	3.3.3 <i>Indian national forest inventory (NFI)</i>	3-141
162	3.3.4 <i>Key references for Section 3.3</i>	3-144
163	3.4 DATA COLLECTION AT LOCAL / NATIONAL LEVEL.....	3-146
164	3.4.1 <i>Scope of Chapter: rationale for community based inventories</i>	3-146
165	3.4.2 <i>How communities can make their own forest inventories</i>	3-149
166	3.4.3 <i>Additional data requirements</i>	3-153
167	3.4.4 <i>Reliability and accuracy</i>	3-153
168	3.4.5 <i>Costs</i>	3-155
169	3.4.6 <i>Options for independent assessment of locally collected data</i>	3-155
170	3.4.7 <i>Options for independent assessment of locally collected data</i>	3-156
171	3.5 RECOMMENDATIONS FOR COUNTRY CAPACITY BUILDING.....	3-157
172	3.5.1 <i>Scope of chapter</i>	3-157
173	3.5.2 <i>Building National Carbon Monitoring Systems For REDD: Elements and Capacities</i>	3-157
174	3.5.3 <i>Capacity gaps and cost implications</i>	3-166
175	3.5.4 <i>Key references for section 3.5</i>	3-171
176	4 GUIDANCE ON REPORTING.....	4-173
177	4.1 SCOPE OF CHAPTER.....	4-173
178	4.1.1 <i>The importance of good reporting</i>	4-173
179	4.1.2 <i>Overview of the Chapter</i>	4-173
180	4.2 OVERVIEW OF REPORTING PRINCIPLES AND PROCEDURES.....	4-173
181	4.2.1 <i>Current reporting requirements under the UNFCCC</i>	4-173
182	4.2.2 <i>Inventory and reporting principles</i>	4-174
183	4.2.3 <i>Structure of a GHG inventory</i>	4-175
184	4.3 WHAT ARE THE MAJOR CHALLENGES FOR DEVELOPING COUNTRIES?.....	4-178
185	4.4 THE CONSERVATIVENESS APPROACH.....	4-179
186	4.4.1 <i>Addressing incomplete estimates</i>	4-181
187	4.4.2 <i>Addressing uncertain estimates</i>	4-181
188	4.4.3 <i>Conclusion: conservativeness is a win-win option</i>	4-183
189	4.5 KEY REFERENCES FOR CHAPTER 4.....	4-184
190		

191 **1 INTRODUCTION**

192 **1.1 PURPOSE AND SCOPE OF THE SOURCEBOOK**

193 This sourcebook is designed to be a guide to develop a reference emission and design a
194 system for monitoring and estimating carbon dioxide emissions from deforestation and
195 forest degradation at the national scale, based on the general requirements set by the
196 United Nation Framework Convention on Climate Change (UNFCCC) and the specific
197 methodologies for the land use and forest sectors provided by the Intergovernmental
198 Panel on Climate Change (IPCC).

199 The sourcebook introduces users to: i) the key issues and challenges related to
200 monitoring and estimating carbon emissions from deforestation and forest degradation;
201 ii) the key methods provided in the 2003 IPCC Good Practice Guidance for Land Use,
202 Land Use Change and Forestry (GPG-LULUCF) and the 2006 IPCC Guidelines for National
203 Greenhouse Gas Inventories for Agriculture, Forestry and Other Land Uses (GL-AFOLU);
204 iii) how these IPCC methods provide the steps needed to estimate emissions from
205 deforestation and forest degradation and iv) the key issues and challenges related to
206 reporting the estimated emissions.

207 The sourcebook provides transparent methods and procedures that are designed to
208 produce accurate estimates of changes in forest area and carbon stocks and resulting
209 emissions of carbon dioxide from deforestation and degradation, in a format that is user-
210 friendly. It is intended to complement the GPG-LULUCF and AFOLU by providing
211 additional explanation, clarification and enhanced methodologies for obtaining and
212 analyzing key data.

213 The sourcebook is not designed as a primer on how to analyze remote sensing data nor
214 how to collect field measurements of forest carbon stocks as it is expected that the users
215 of this sourcebook would have some expertise in either of these areas.

216 The sourcebook was developed considering the following guiding principles:

- 217 **Relevance:** Any monitoring system should provide an appropriate match between
218 known REDD policy requirements and current technical capabilities. Further
219 methods and technical details can be specified and added with evolving political
220 negotiations and decisions.
- 221 **Comprehensiveness:** The system should allow global applicability with
222 implementation at the national level, and with approaches that have potential for
223 sub-national activities.
- 224 **Consistency:** Efforts have to consider previous related UNFCCC efforts and
225 definitions.
- 226 **Efficiency:** Proposed methods should allow cost-effective and timely
227 implementation, and support early actions.
- 228 **Robustness:** Monitoring should provide appropriate results based on sound
229 scientific underpinnings and international technical consensus among expert
230 groups.
- 231 **Transparency:** The system must be open and readily available for third party
232 reviewers and the methodology applied must be replicable.

233

234 **1.2 ISSUES AND CHALLENGES**

235 The permanent conversion of forested to non-forested areas in developing countries has
236 had a significant impact on the accumulation of greenhouse gases in the atmosphere¹, as
237 has forest degradation caused by high impact logging, over-exploitation for fuelwood,
238 intense grazing that reduces regeneration, wildfires, and forest fragmentation. If the
239 emissions of methane (CH₄), nitrous oxide (N₂O), and other chemically reactive gases
240 that result from subsequent uses of the land are considered in addition to carbon dioxide
241 (CO₂) emissions, annual emissions from tropical deforestation during the 1990s
242 accounted for about 15-25% of the total anthropogenic emissions of greenhouse gases².

243 For a number of reasons, activities to reduce such emissions are not accepted for
244 generating creditable emissions reductions under the Kyoto Protocol. However, the
245 compelling environmental rationale for their consideration has been crucial for the recent
246 inclusion of the REDD issue (i.e., "Reducing Emissions from Deforestation and Forest
247 Degradation in developing countries") in the UNFCCC agenda for a future global climate
248 agreement³. Although existing IPCC methodologies and UNFCCC reporting principles will
249 represent the basis of any future REDD mechanism, fundamental methodological issues
250 need to be urgently addressed in order to produce estimates that are "results based,
251 demonstrable, transparent, and verifiable, and estimated consistently over time"⁴ - this
252 is the focus of this sourcebook.

253 **1.2.1 LULUCF in the UNFCCC and Kyoto Protocol**

254 Under the current rules for Annex I (i.e. industrialized) countries, the Land Use, Land
255 Use Change and Forestry (LULUCF) sector is the only sector where the requirements for
256 reporting emissions and removals are different between the UNFCCC and the Kyoto
257 Protocol (Table 1.2.1). Indeed, unlike the reporting under the Convention - which
258 includes all emissions/removals from LULUCF -, under the Kyoto Protocol the reporting
259 and accounting of emissions/removals is mandatory only for the activities under Art. 3.3,
260 while it is voluntary (i.e. eligible) for activities under Art. 3.4 (see Table 1.2.1). These
261 LULUCF activities may be developed domestically by Annex I countries or via Kyoto
262 Protocol's flexible instruments, including Afforestation/Reforestation projects under the
263 "Clean Development Mechanism" (CDM) in non-Annex I (i.e. developing) countries. For
264 the national inventories, estimating and reporting guidelines can be drawn from UNFCCC
265 documents⁵, the 1996 IPCC (revised) Guidelines, the 2003 Good Practice Guidance for
266 LULUCF (GPG-LULUCF; Chapter 3 for UNFCCC reporting and Chapter 4 for methods
267 specific to the Kyoto Protocol reporting).

268 The IPCC has also adopted a more recent set of estimation guidelines (2006 Guidelines)
269 in which the Agriculture and LULUCF sectors are integrated to form the Agriculture, Land
270 Use and Forestry (AFOLU) sector. Although these latest Guidelines should still be
271 considered only a scientific publication, because the decision of their use for reporting
272 under UNFCCC has not been taken yet, in this sourcebook we make frequent references
273 to them (as GL-AFOLU) because they represent a relevant and updated source of
274 methodological information.

275

¹ De Fries et al. (2002); Houghton (2003); Achard et al. (2004)

² According to the IPCC AR4 (2007), 1.6 ± 0.9 GtC yr⁻¹ are emitted from land use changes (mainly tropical deforestation)

³ Decision -/CP.13, http://unfccc.int/files/meetings/cop_13/application/pdf/cp_bali_action.pdf

⁴ Decision -/CP.13. http://unfccc.int/files/meetings/cop_13/application/pdf/cp_redd.pdf.

⁵ For a broader overview of reporting principles and procedures under UNFCCC see Chapter 6.2.

277 **Table 1.2.1:** Existing frameworks for the Land Use, Land Use Change and Forestry
 278 (LULUCF) sector under the UNFCCC and the Kyoto Protocol.

Land Use, Land Use Change and Forestry		
UNFCCC (2003 GPG and 2006 GL-AFOLU)	Kyoto	Kyoto-Flexibility
Six land use classes and conversion between them: Forest lands Cropland Grassland Settlements Wetlands Other Land	Article 3.3 Afforestation, Reforestation, Deforestation Article 3.4 Cropland management Grazing land management Forest management Revegetation	CDM Afforestation Reforestation
Deforestation= forest converted to another land category	Controlled by the Rules and Modalities (including Definitions) of the Marrakesh Accords	

279 **1.2.2 Definition of Forests, Deforestation and Degradation**

280 For the new REDD mechanism, many terms, definitions and other elements are not yet
 281 clear. For example, although the terms 'deforestation' and 'forest degradation' are
 282 commonly used, they can widely vary among countries. As decisions for REDD will likely
 283 build on the current modalities under the UNFCCC and its Kyoto Protocol, current
 284 definitions and terms potentially represent a starting point for considering refined and/or
 285 additional definitions, if it will be needed.

286 For this reason, the definitions as used in UNFCCC and Kyoto Protocol context,
 287 potentially applicable to REDD after a negotiation process, are described below.
 288 Specifically, while for reporting under the UNFCCC only generic definitions on land uses
 289 were agreed on, the Marrakesh Accords (MA) prescribed a set of more specific definitions
 290 to be applied for LULUCF activities the Kyoto Protocol, although some flexibility is left to
 291 countries.

292 **Forest land** – Under the UNFCCC, this category includes all land with woody vegetation
 293 consistent with thresholds used to define Forest Land in the national greenhouse gas
 294 inventory. It also includes systems with a vegetation structure that does not, but *in situ*
 295 could potentially reach, the threshold values used by a country to define the Forest Land
 296 category. Moreover, forest use should be the predominant use rather than other uses⁶.

297 The estimation of deforestation is affected by the definitions of 'forest' versus 'non-
 298 forest' area that vary widely in terms of tree size, area, and canopy density. Forest
 299 definitions are myriad, however, common to most definitions are threshold parameters
 300 including minimum area, minimum height and minimum level of crown cover. In its
 301 forest resource assessment of 2005, the FAO⁷ uses a minimum cover of 10%, height of
 302 5m and area of 0.5ha stating also that forest use should be the predominant use.

⁶ The presence of a predominant forest-use is crucial for land classification since the mere presence of trees is not enough to classify an area as forest land (e.g. an urban park with trees exceeding forest threshold is not considered as a forest land)

⁷ FAO (2006): Global Forest Resources Assessment 2005. Main Report, www.fao.org/forestry/fra2005

303 However, the FAO approach of a single worldwide value excludes variability in ecological
304 conditions and differing perceptions of forests.

305 For the purpose of the Kyoto Protocol⁸, the Marrakech Accords determined that Parties
306 should select a single value of crown area, tree height and area to define forests within
307 their national boundaries. Selection must be from within the following ranges, with the
308 understanding that young stands that have not yet reached the necessary cover or
309 height are included as forest:

310 Minimum forest area: 0.05 to 1 ha

311 Potential to reach a minimum height at maturity *in situ* of 2-5 m

312 Minimum tree crown cover (or equivalent stocking level): 10 to 30 %

313 Under this definition a forest can contain anything from 10% to 100% tree cover; it is
314 only when cover falls below the minimum crown cover as designated by a given country
315 that land is classified as non-forest. However, if this is only a change in the forest cover
316 not followed by a change in use, such as for timber harvest with regeneration expected,
317 the land remains in the forest classification. The specific definition chosen will have
318 implications on where the boundaries between deforestation and degradation occur.

319 The Designated National Authority (DNA) in each country is responsible for the forest
320 definition, and a comprehensive and updated list of each country's DNA and their forest
321 definition can be found on <http://cdm.unfccc.int/DNA/>.

322 The definition of forests offers some flexibility for countries when designing a monitoring
323 plan because analysis of remote sensing data can adapt to different minimum tree crown
324 cover and minimum forest area thresholds. However, consistency in forest classifications
325 for all REDD activities is critical for integrating different types of information including
326 remote sensing analysis. The use of different definitions impacts the technical earth
327 observation requirements and could influence cost, availability of data, and abilities to
328 integrate and compare data through time.

329 **Deforestation** - Most definitions characterize deforestation as the long-term or
330 permanent conversion of land from forest use to other non-forest uses. Under Decision
331 11/CP.7, the UNFCCC defined deforestation as: "...the direct, human-induced conversion
332 of forested land to non-forested land."

333 Effectively this definition means a reduction in crown cover from above the threshold for
334 forest definition to below this threshold. For example, if a country defines a forest as
335 having a crown cover greater than 30%, then deforestation would not be recorded until
336 the crown cover was reduced below this limit. Yet other countries may define a forest as
337 one with a crown cover of 20% or even 10% and thus deforestation would not be
338 recorded until the crown cover was reduced below these limits. If forest cover decreases
339 below the threshold only temporarily due to say logging, and the forest is expected to
340 regrow the crown cover to above the threshold, then this decrease is not considered
341 deforestation.

342 Deforestation causes a change in land use and usually in land cover. Common changes
343 include: conversion of forests to annual cropland, conversion to perennial plants (oil
344 palm, shrubs), conversion to slash-and-burn (shifting cultivation) lands, and conversion
345 to urban lands or other human infrastructure.

346 **Forest degradation** - In areas where there are anthropogenic net emissions during a
347 given time period (i.e. where GHGs emissions are larger than removals) from forests
348 caused by a decrease in canopy cover that does not qualify as deforestation, it is termed
349 as forest degradation.

⁸ UNFCCC (2001): COP-7: The Marrakech accords. (Bonn, Germany: UNFCCC Secretariat)
available at <http://www.unfccc.int>

350 The IPCC special report on 'Definitions and Methodological Options to Inventory
351 Emissions from Direct Human-Induced Degradation of Forests and Devegetation of Other
352 Vegetation Types' (2003) presents five different potential definitions for degradation
353 along with their pros and cons. The report suggested the following characterization for
354 degradation:

355 "A direct, human-induced, long-term loss (persisting for X years or more) or at least Y%
356 of forest carbon stocks [and forest values] since time T and not qualifying as
357 deforestation".

358 The thresholds for carbon loss and minimum area affected as well as long term need to
359 be specified to operationalize this definition. In terms of changes in carbon stocks,
360 degradation therefore would represent a human-induced decrease in carbon stocks, with
361 measured canopy cover remaining above the threshold for definition of forest and no
362 change in land use. Moreover, to be distinguished from forestry activities the decrease
363 should be considered persistent. The persistence could be evaluated by monitoring
364 carbon stock changes either over time (i.e. a net decrease during a given period, e.g. 20
365 years) or along space (e.g. a net decrease over a large area where all the successional
366 stages of a managed forest are present).

367 Considering that, at national level, sustainable forest management leads to national
368 gross losses of carbon stocks (e.g. through harvesting) which can be only lower than (or
369 equal to) national gross gains (in particular through forest growth), consequently a net
370 decrease of forest carbon stocks at national level during a reporting period would be due
371 to forest degradation within the country. Conversely, a net increase of forest carbon
372 stocks at national level would correspond to forest enhancement.

373 Therefore, it is also possible that no specific definition is needed, and that any net
374 emission will be reported simply as a net decrease of carbon stock in the category
375 "Forest land remaining forest land".

376 Given the lack of a clear definition for degradation, or even the lack of any definition, it
377 is difficult to design a monitoring system. However, some general observations and
378 concepts exist and are presented here to inform the debate. Degradation may present a
379 much broader land cover change than deforestation. In reality, monitoring of
380 degradation will be limited by the technical capacity to sense and record the change in
381 canopy cover because small changes will likely not be apparent unless they produce a
382 systematic pattern in the imagery.

383 Many activities cause degradation of carbon stocks in forests but not all of them can be
384 monitored well with high certainty, and not all of them need to be monitored using
385 remote sensing data, though being able to use such data would give more confidence to
386 reported emissions from degradation. To develop a monitoring system for degradation, it
387 is first necessary that the causes of degradation be identified and the likely impact on
388 the carbon stocks be assessed.

389 Area of forests undergoing selective logging (both legal and illegal) with the
390 presence of gaps, roads, and log decks are likely to be observable in remote
391 sensing imagery, especially the network of roads and log decks. The gaps in the
392 canopy caused by harvesting of trees have been detected in imagery such as
393 Landsat using more sophisticated analytical techniques of frequently collected
394 imagery, and the task is somewhat easier to detect when the logging activity is
395 more intense (i.e. higher number of trees logged; see Section 2.1.2). A
396 combination of legal logging followed by illegal activities in the same concession is
397 likely to cause more degradation and more change in canopy characteristics, and
398 an increased chance that this could be monitored with Landsat type imagery and
399 interpretation. The reduction in carbon stocks from selective logging can also be
400 estimated without the use satellite imagery, i.e. based on methods given in the
401 IPCC GL-AFOLU for estimating changes in carbon stocks of "forest land remaining
402 forest land".

- 403 □ Degradation of carbon stocks by forest fires could be more difficult to monitor
 404 with existing satellite imagery and little to no data exist on the changes in carbon
 405 stocks. Depending on the severity and extent of fires, the impact on the carbon
 406 stocks could vary widely. In practically all cases for tropical forests, the cause of
 407 fire will be human induced as there are little to no dry electric storms in tropical
 408 humid forest areas.
- 409 □ Degradation by over exploitation for fuel wood or other local uses of wood is often
 410 followed by animal grazing that prevents regeneration, a situation more common
 411 in drier forest areas. This situation is likely not to be detectable from satellite
 412 image interpretation unless the rate of degradation was intense causing larger
 413 changes in the canopy.
- 414 □ Invasion by alien or exotic species into already degraded forests can exacerbate
 415 the process as they can reduce natural forest regrowth. Exotic species replacing
 416 indigenous species are often more prone to further degradation (natural or
 417 anthropogenic) and can generally reproduce more prolifically. Whether the area
 418 of this type of degradation could be monitored over time with satellite imagery
 419 depends on whether the invasions cause a marked change in the canopy
 420 characteristics.

421 **1.2.3 General Method for Estimating CO₂ Emissions**

422 To facilitate the use of the IPCC GL-AFOLU and GPG reports side by side with the
 423 sourcebook, definitions used in the sourcebook remain consistent with the IPCC
 424 Guidelines. In this section we summarize key guidance and definitions from the IPCC
 425 Guidelines that frame the more detailed procedures that follow.

426 The term “Categories” as used in IPCC reports refers to specific sources of
 427 emissions/removals of greenhouse gases. For the purposes of this sourcebook, the
 428 following categories are considered under the AFOLU sector:

- 429 □ Forest Land converted to Crop Land, Forest Land converted to Grass Land, Forest
 430 Land converted to Settlements, Forest Land converted to Wetlands, and Forest
 431 Land converted to Other Land are commonly equated with “deforestation”.
- 432 □ A decrease in carbon stocks of Forest Land remaining Forest Land is commonly
 433 equated to “forest degradation”.

434 The IPCC Guidelines refer to two basic inputs with which to calculate greenhouse gas
 435 inventories: activity data and emissions factors. “Activity data” refer to the extent of an
 436 emission/removal category, and in the case of deforestation and forest degradation
 437 refers to the areal extent of those categories, presented in hectares. Henceforth for the
 438 purposes of this sourcebook, activity data are referred to as area change data. “Emission
 439 factors” refer to emissions/removals of greenhouse gases per unit area, e.g. tons carbon
 440 dioxide emitted per hectare of deforestation. Emissions/removals resulting from land-use
 441 conversion are manifested in changes in ecosystem carbon stocks, and for consistency
 442 with the IPCC Guidelines, we use units of carbon, specifically metric tons of carbon per
 443 hectare (t C ha⁻¹), to express emission factors for deforestation and forest degradation.

444 **1.2.3.1 Assessing activity data**

445 The IPCC Guidelines describe three different **Approaches** for representing the activity
 446 data, or the change in area of different land categories (Table 1.2.2): Approach 1
 447 identifies the total area for each land category - typically from non-spatial country
 448 statistics - but does not provide information on the nature and area of conversions
 449 between land uses, i.e. it only provides “net” area changes (i.e. deforestation minus
 450 afforestation) and thus is not suitable for REDD. Approach 2 involves tracking of land
 451 conversions between categories, resulting in a non-spatially explicit land-use conversion
 452 matrix. Approach 3 extends Approach 2 by using spatially explicit land conversion

453 information, derived from sampling or wall-to-wall mapping techniques. Similarly to
 454 current requirements under the Kyoto Protocol, it is likely that under a REDD mechanism
 455 that land use changes will be required to be identifiable and traceable in the future, i.e. it
 456 is likely that only Approach 3 can be used for REDD implementation⁹.

457 **Table 1.2.2:** A summary of the Approaches that can be used for the activity data.

Approach for activity data: Area change
1. total area for each land use category, but no information on conversions (only net changes)
2. tracking of conversions between land-use categories (only between 2 points in time)
3. spatially explicit tracking of land-use conversions over time

458

459 1.2.3.2 Assessing emission factors

460 The emission factors are derived from assessments of the changes in carbon stocks in
 461 the various carbon pools of a forest. Carbon stock information can be obtained at
 462 different **Tier levels** (Table 1.2.3) and which one is selected is independent of the
 463 Approach selected. Tier 1 uses IPCC default values (i.e. biomass in different forest
 464 biomes, carbon fraction etc.); Tier 2 requires some country-specific carbon data (i.e.
 465 from field inventories, permanent plots), and Tier 3 highly disaggregated national
 466 inventory-type data of carbon stocks in different pools and assessment of any change in
 467 pools through repeated measurements also supported by modeling. Moving from Tier 1
 468 to Tier 3 increases the accuracy and precision of the estimates, but also increases the
 469 complexity and the costs of monitoring.

470 **Table 1.2.3:** A summary of the Tiers that can be used for the emission factors.

Tiers for emission factors: Change in C stocks
1. IPCC default factors
2. Country specific data for key factors
3. Detailed national inventory of key C stocks, repeated measurements of key stocks through time or modeling

471

472 **Chapter 2.1 of this sourcebook provides guidance on how to obtain the activity**
 473 **data, or gross change in forest area, with low uncertainty. Chapter 2.2 focuses**
 474 **on obtaining data for emission factors and providing guidance on how to**
 475 **produce estimates of carbon stocks of forests with low uncertainty suitable for**
 476 **national assessments.**

477 According to the IPCC, estimates should be accurate and uncertainties should be
 478 quantified and reduced as far as practicable. Furthermore, carbon stocks of the key or
 479 significant categories and pools should be estimated with the higher tiers (see also

⁹ While both Approaches 2 and 3 give gross-net changes among land categories, only Approach 3 allows to estimate gross-net changes within a category, i.e. to detect a deforestation followed by an afforestation, which is not possible with Approach 2 unless detailed supplementary information is provided.

480 chapter 3.1.5). As the reported estimates of reduced emissions will likely be the basis of
481 an accounting procedure (as in the Kyoto Protocol), with the eventual assignment of
482 economic incentives, Tier 3 should be the level to which countries should aspire. In the
483 context of REDD, however, the methodological choice will inevitably result from a
484 balance between the requirements of accuracy/precision and the cost of monitoring. It is
485 likely that this balance will be guided by the principle of **conservativeness**, i.e. a tier
486 lower than required could be used – or a carbon pool could be ignored - if it can be
487 demonstrated that the overall estimate of reduced emissions are likely to be
488 underestimated (see also chapter 4). Thus, when accuracy and precision of the
489 estimates cannot be achieved, estimates of reduced emissions should *at least* be
490 conservative, i.e. with very low probability to be overestimated.

491 **1.2.4 Reference Emissions Levels and Benchmark Forest Area Map**

492 The estimate of reductions in emissions from deforestation and degradation requires
493 assessing reference emissions levels against which future emissions can be compared.
494 These reference levels represent the historical emissions from deforestation and forest
495 degradation in “forested land” at a national level.

496 Credible reference levels of emissions can be established for a REDD system using
497 existing scientific and technical tools, and this is the focus of this sourcebook.

498 Technically, from remote sensing imagery it is possible to monitor forest area change
499 with confidence from 1990s onwards and estimates of forest C stocks can be obtained
500 from a variety of sources. Feasibility and accuracies will strongly depend on national
501 circumstances (in particular in relation to data availability), that is, potential limitations
502 are more related to resources and data availability than to methodologies.

503 A related issue is the concept of a **benchmark forest area map**. Any national program
504 to reduce emissions from deforestation and degradation will need to have an initial forest
505 area map to represent the point from which each future forest area assessment will be
506 made and actual changes will be monitored so as to report only gross deforestation
507 going forward. This initial forest area map is referred to here as a benchmark map. This
508 implies that an agreement will be needed by Parties on deciding on a benchmark year
509 against which all future deforestation and degradation will be measured. The use of a
510 benchmark map will show where monitoring should be done to assess changes in forest
511 cover.

512 The use of a benchmark map makes monitoring deforestation (and some degradation) a
513 simpler task. The interpretation of the remote sensing imagery needs to identify only the
514 areas (or pixels) that changed compared to the benchmark map. The benchmark map
515 would then be updated at the start of each new analysis event so that one is just
516 monitoring the loss of forest area from the original benchmark map. The forest area
517 benchmark map would also show where forests exist and how they are stratified either
518 for carbon or for other national needs.

519

520 If only gross deforestation is being monitored, the benchmark map can be updated by
521 subtracting the areas where deforestation has occurred. If reforestation needs to be
522 monitored, the entire area in the original benchmark map needs to be monitored for
523 both forest loss and forest gain. To show where non-forest land is reverting to forests a
524 monitoring of the full country territory is needed.

525

526

527

528 **1.2.5 Roadmap for the Sourcebook**

529 The sourcebook is organized as follows:

530

531 Chapter 2: METHODOLOGICAL SECTION

532 Chapter 3: PRACTICAL EXAMPLES FOR DATA COLLECTION

533 Chapter 4: REPORTING

534

535

536 The **Methodological Section** (Chapter 2) is organized as follows:

537 2.1 Guidance on monitoring changes in forest area

538 2.1.1 Monitoring of changes of forest areas - deforestation and
539 reforestation

540 2.1.2 Monitoring of forest area changes within forests – forest land
541 remaining forests land

542 2.2 Estimation of above ground carbon stocks

543 2.3 Estimation of soil carbon stocks

544 2.4 Methods for estimating CO₂ emissions from deforestation and forest
545 degradation

546 2.5 Methods for estimating GHG's emissions from biomass burning

547 2.6 Estimation of uncertainties

548 2.7 Status of evolving technologies

549

550 The **data collection section** (Chapter 3) is presenting Practical Examples with
551 recommendations for capacity building and is organized as follows:

552 3.1 Overview of annex-I GHG's national inventories on LULUCF

553 3.2 Overview of the existing forest area changes monitoring systems

554 3.3 National forest inventories

555 3.4 Data collection at local / national level

556 3.5 Recommendations for country capacity building

557

558 Chapter 4 is presenting the **reporting practices**.

559

560

561

562 2 METHODOLOGICAL SECTION

563 2.1 GUIDANCE ON MONITORING OF CHANGES IN FOREST 564 AREA

565 Frédéric Achard, Joint Research Centre, Italy.

566 Gregory P. Asner, Carnegie Institution, Stanford, USA

567 Ruth De Fries, Columbia University, USA

568 Martin Herold, Friedrich Schiller University Jena, Germany

569 Danilo Mollicone, Food and Agriculture Organization, Italy

570 Devendra Pandey, Forest Survey of India, India

571 Carlos Souza Jr., IMAZON, Brazil

572 2.1.1 Scope of chapter

573 **Chapter 2.1 presents the state of the art for data and approaches to be used for**
574 **monitoring forest area changes at the national scale in tropical countries using**
575 **remote sensing imagery. It includes approaches and data for monitoring**
576 **changes of forest areas (i.e. deforestation and reforestation) and for**
577 **monitoring of changes within forest land (i.e. forest land remaining forests**
578 **land, e.g. degradation). It includes general recommendations (e.g. for**
579 **establishing historical reference scenarios) and detailed recommended steps**
580 **for monitoring changes of forest areas or in forest areas.**

581 The chapter presents the minimum requirements to develop first order national forest
582 area change databases, using typical and internationally accepted methods. There are
583 more advanced and costly approaches that may lead to more accurate results and would
584 meet the reporting requirements, but they are not presented here.

585

586 The remote sensing techniques can be used for two purposes: (i) to monitor changes in
587 forest areas (i.e. from forest to non forest land – deforestation – and from non forest
588 land to forest land - reforestation) and (ii) to monitor area changes within forest land
589 which leads to changes in carbon stocks (e.g. degradation). The techniques to monitor
590 changes in forest areas (e.g. deforestation) provide high-accuracy ‘activity data’ (i.e.
591 area estimates) and can also allow reducing the uncertainty of emission factors through
592 spatial mapping of main forest ecosystems. Monitoring of reforestation area has greater
593 uncertainty than monitoring deforestation. The techniques to monitor changes within
594 forest land (which leads to changes in carbon stocks) provide lower accuracy ‘activity
595 data’ and gives poor complementary information on emission factors.

596

597 Section 2.1.2 describes the remote sensing techniques to monitor changes in forest
598 areas (i.e. deforestation and expansion of forest area).

599 Section 2.1.3 focuses on monitoring area changes within forest land which leads to
600 reduction in carbon stocks (i.e. degradation). Techniques to monitor changes within
601 forest land which leads to increase of carbon stocks (e.g. through forest management)
602 are not considered in the present version.

603

604

605

606 **2.1.2 Monitoring of changes of forest areas - deforestation and** 607 **reforestation**

608 **2.1.2.1 General recommendation for establishing a historical reference scenario**

609 As minimum requirement, it is recommended to use Landsat-type remote sensing data
610 (30 m resolution) for years 1990, 2000 and 2005 for monitoring forest cover changes
611 with 1 to 5 ha Minimum Mapping Unit (MMU). It might be necessary to use data from a
612 year prior or after 1990, 2000, and 2005 due to availability and cloud contamination.
613 These data will allow assessing changes of forest areas (i.e. to derive area deforested
614 and forest regrowth for the period considered) and, if desired, producing a map of
615 national forest area (to derive deforestation rates) using a common forest definition. A
616 hybrid approach combining automated digital segmentation and/or classification
617 techniques with visual interpretation and/or validation of the resulting classes/polygons
618 should be preferred as simple, robust and cost effective method.

619 There may be different spatial units for the detection of forest and of forest change.
620 Remote sensing data analyses become more difficult and more expensive with smaller
621 Minimum Mapping Units (MMU) i.e. more detailed MMU's increase mapping efforts and
622 usually decrease change mapping accuracy. There are several MMU examples from
623 current national and regional remote sensing monitoring systems: Brazil PRODES system
624 for monitoring deforestation (6.25 ha initially¹⁰, now 1 ha for digital processing), India
625 national forest monitoring (1 ha), EU-wide CORINE land cover/land use change
626 monitoring (5 ha), 'GMES Service Element' Forest Monitoring (0.5 ha), and Conservation
627 International national case studies (2 ha).

628 **2.1.2.2 Key features**

629 Presently the only free global mid-resolution (30m) remote sensing imagery are from
630 NASA (Landsat satellites) for around years 1990, 2000, and 2005 (the mid-decadal
631 dataset 2005/2006 has just been completed) with some quality issues in some parts of
632 the tropics (clouds, seasonality, etc). All Landsat data from US archive (USGS) are
633 available for free since the end of 2008. Brazilian/Chinese remote sensing imagery from
634 the CBERS satellites is also now freely available in developing countries.

635 The period 2000-2005 is more representative of recent historical changes and potentially
636 more suitable due to the availability of complementary data during a recent time frame.

637 Specifications on minimum requirements for image interpretation are:

- 638 Geo-location accuracy < 1 pixel, i.e. < 30m,
- 639 Minimum mapping unit should be between 1 and 6 ha,
- 640 A consistency assessment should be carried out.

641 **2.1.2.3 Recommended steps**

642 The following steps are needed for a national assessment that is scientifically credible
643 and can be technically accomplished by in-country experts:

- 644 1. Selection of the approach:

¹⁰ The PRODES project of Brazilian Space Agency (INPE) has been producing annual rates of gross deforestation since 1988 using a minimum mapping unit of 6.25 ha. PRODES does not include reforestation.

- 645 a. Assessment of national circumstances, particularly existing definitions
646 and data sources
647 b. Definition of change assessment approach by deciding on:
648 i. Satellite imagery
649 ii. Sampling versus wall to wall coverage
650 iii. Fully visual versus semi-automated interpretation
651 iv. Accuracy or consistency assessment
652 c. Plan and budget monitoring exercise including:
653 i. Hard and Software resources
654 ii. Requested Training
655 2. Implementation of the monitoring system:
656 a. Selection of the forest definition
657 b. Designation of forest area for acquiring satellite data
658 c. Selection and acquisition of the satellite data
659 d. Analysis of the satellite data (preprocessing and interpretation)
660 e. Assessment of the accuracy
661

662 **2.1.2.4 Selection and Implementation of a Monitoring Approach**

663 **2.1.2.4.1 Step 1: Selection of the forest definition**

664 Currently Annex I Parties use the UNFCCC framework definition of forest and
665 deforestation adopted for implementation of Article 3.3 and 3.4 (see section 1.2.2) and,
666 without other agreed definition, this definition is considered here as the working
667 definition. Sub-categories of forests (e.g. forest types) can be defined within the
668 framework definition of forest.

669 Remote sensing imagery allows land cover information only to be obtained. Local expert
670 or field information is needed to derive land use estimates.

671 **2.1.2.4.2 Step 2: Designation of forest area for acquiring satellite data**

672 Many types of land cover exist within national boundaries. REDD monitoring needs to
673 cover all forest areas and the same area needs to be monitored for each reporting
674 period. If the REDD mechanism is only related to decreases in forest area it will not be
675 necessary or practical in many cases to monitor the entire national extent that includes
676 non-forest land types. Therefore, a forest mask can be designated initially to identify the
677 area to be monitored for each reporting period (referred to in Section 1.2.2 as the
678 benchmark map).

679 Ideally, wall-to-wall assessments of the entire national extent would be carried out to
680 identify forested area according to UNFCCC forest definitions at the beginning and end of
681 the reference and assessment periods (to be decided by the Parties to the UNFCCC). This
682 approach may not be practical for large countries. Existing forest maps at appropriate
683 spatial resolution and for a relatively recent time could be used to identify the overall
684 forest extent.

685

Important principles in identifying the overall forest extent are:

686

687

- 688 The area should include all forests within the national boundaries
- 689 A consistent overall forest extent should be used for monitoring all forest changes
690 during assessment period

690

691

692 **2.1.2.4.3 Step 3: Selection of satellite imagery and coverage**

693 Fundamental requirements of national monitoring systems are that they measure
 694 changes throughout all forested area, use consistent methodologies at repeated intervals
 695 to obtain accurate results, and verify results with ground-based or very high resolution
 696 observations. The only practical approach for such monitoring systems is through
 697 interpretation of remotely sensed data supported by ground-based observations. Remote
 698 sensing includes data acquired by sensors on board aircraft and space-based platforms.
 699 Multiple methods are appropriate and reliable for forest monitoring at national scales.

700 Many data from optical sensors at a variety of resolutions and costs are available for
 701 monitoring deforestation (Table 2.1.1).

702

703 **Table 2.1.1: Utility of optical sensors at multiple resolutions for deforestation**
 704 **monitoring**

Sensor & resolution	Examples of current sensors	Minimum mapping unit (change)	Cost	Utility for monitoring
Coarse (250-1000 m)	SPOT-VGT (1998-) Terra-MODIS (2000-) Envisat-MERIS (2004 -)	~ 100 ha ~ 10-20 ha	Low or free	Consistent pan-tropical annual monitoring to identify large clearings and locate "hotspots" for further analysis with mid resolution
Medium (10-60 m)	Landsat TM or ETM+, Terra-ASTER IRS AWiFs or LISS III CBERS HRCCD DMC SPOT HRV	0.5 - 5 ha	Landsat & CBERS are free from 2009 <\$0.001/km ² for historical data \$0.02/km ² to \$0.5/km ² for recent data	Primary tool to map deforestation and estimate area change
Fine (<5 m)	IKONOS QuickBird Aerial photos	< 0.1 ha	High to very high \$2 -30 /km ²	Validation of results from coarser resolution analysis, and training of algorithms

705

706 **Availability of medium resolution data**

707 The USA National Aeronautics and Space Administration (NASA) launched a satellite with
 708 a mid-resolution sensor that was able to collect land information at a landscape scale.
 709 ERTS-1 was launched on July 23, 1972. This satellite, renamed 'Landsat', was the first in
 710 a series (seven to date) of Earth-observing satellites that have permitted continuous
 711 coverage since 1972. Subsequent satellites have been launched every 2-3 years. Still in
 712 operation Landsat 5 and 7 cover the same ground track repeatedly every 16 days.

713 Almost complete global coverages from these Landsat satellites are available at low or
 714 no cost for early 1990s, early 2000s and around year 2005 from NASA¹¹, the USGS¹², or
 715 from the University of Maryland's Global Land Cover Facility¹³. These data serve a key

¹¹ <https://zulu.ssc.nasa.gov/mrsid>

¹² http://edc.usgs.gov/products/satellite/landsat_ortho.html

¹³ <http://glcfapp.umiacs.umd.edu/>

716 role in establishing historical deforestation rates, though in some parts of the humid
717 tropics (e.g. Central Africa) persistent cloudiness is a major limitation to using these
718 data. Until year 2003, Landsat, given its low cost and unrestricted license use, has been
719 the workhorse source for mid-resolution (10-50 m) data analysis.

720 On April 2003, the Landsat 7 ETM+ scan line corrector failed resulting in data gaps
721 outside of the central portion of acquired images, seriously compromising data quality
722 for land cover monitoring. Given this failure, users would need to explore how the
723 ensuing data gap might be filled at a reasonable cost with alternative sources of data in
724 order to meet the needs for operational decision-making.

725 Alternative sources of data include Landsat-5, ASTER, SPOT, IRS, CBERS or DMC data
726 (Table 2.1.2). NASA, in collaboration with USGS, initiated an effort to acquire and
727 compose appropriate imagery to generate a mid-decadal (around years 2005/2006) data
728 set from such alternative sources. The combined Archived Coverage in EROS Archive of
729 the Landsat 5 TM and Landsat-7 ETM+ reprocessed-fill product for the years 2005/2006
730 covers more than 90% of the land area of the Earth. These data have been processed to
731 a new orthorectified standard using data from NASA's Shuttle Radar Topography Mission.

732 The USGS has established a no charge Web access to the full Landsat USGS archive¹⁴.
733 The full Landsat 7 ETM+ USGS archive (since 1999) and all USGS archived Landsat 5 TM
734 data (since 1984), Landsat 4 TM (1982-1985) and Landsat 1-5 MSS (1972-1994) are
735 now available for ordering at no charge.

736 During the selection of the scenes to use in any assessment, seasonality of climate has
737 to be considered: in situations where seasonal forest types (i.e. a distinct dry season
738 where trees may drop their leaves) exist more than one scene should be used. Inter-
739 annual variability has to be considered based on climatic variability.

740

¹⁴ http://ldcm.usgs.gov/pdf/Landsat_Data_Policy.pdf

Table 2.1.2: Present availability of optical mid-resolution (10-60 m) sensors

Nation	Satellite & sensor	Resolution & coverage	Cost for data acquisition (archive ¹⁵)	Feature
USA	Landsat-5 TM	30 m 180×180 km ²	600 US\$/scene 0.02 US\$/km ² All US archived data will be free from 2009	Images every 16 days to any satellite receiving station. Operating beyond expected lifetime.
USA	Landsat-7 ETM+	30 m 60×180 km ²	600 US\$/scene 0.06 US\$/ km ² All US archived data will be free from end 2008	On April 2003 the failure of the scan line corrector resulted in data gaps outside of the central portion of images, seriously compromising data quality
USA/ Japan	Terra ASTER	15 m 60×60 km ²	60 US\$/scene 0.02 US\$/km ²	Data is acquired on request and is not routinely collected for all areas
India	IRS-P2 LISS-III & AWIFS	23.5 & 56 m		After an experimental phase, AWIFS images can be acquired on a routine basis.
China/ Brazil	CBERS-2 HRCCD	20 m	Free in Brazil and potentially for other developing countries	Experimental; Brazil uses on-demand images to bolster their coverage.
Algeria/ China/ Nigeria/ Turkey/ UK	DMC	32 m 160×660 km ²	3000 €/scene 0.03 €/km ²	Commercial; Brazil uses alongside Landsat data
France	SPOT-5 HRVIR	10-20 m 60×60 km ²	2000 €/scene 0.5 €/km ²	Commercial Indonesia & Thailand used alongside Landsat data

742

743 Optical mid-resolution data have been the primary tool for deforestation monitoring.
 744 Other, newer, types of sensors, e.g. Radar (ERS1/2 SAR, JERS-1, ENVISAT-ASAR and
 745 ALOS PALSAR) and Lidar, are potentially useful and appropriate. Radar, in particular,
 746 alleviates the substantial limitations of optical data in persistently cloudy parts of the
 747 tropics. Data from Lidar and Radar have been demonstrated to be useful in project
 748 studies, but so far, they are not widely used operationally for forest monitoring over
 749 large areas. Over the next five years or so, the utility of radar may be enhanced
 750 depending on data acquisition, access and scientific developments.

751 In summary, Landsat-type data around years 1990, 2000 and 2005 will most suitable to
 752 assess historical rates and patterns of deforestation.

753

¹⁵ Some acquisitions can be programmed (e.g., DMC, SPOT). The cost of programmed data is generally at least twice the cost of archived data. Costs relate to acquisition costs only. They do not include costs for data processing and for data analysis.

754 **Utility of coarse resolution data**

755 Coarse resolution (250 m – 1km) data are available from 1998 (SPOT-VGT) or 2000
756 (MODIS). Although the spatial resolution is coarser than Landsat-type sensors, the
757 temporal resolution is daily, providing the best possibility for cloud-free observations.
758 The higher temporal resolution increases the likelihood of cloud-free images and can
759 augment data sources where persistent cloud cover is problematic. Coarse resolution
760 data also has cost advantages, offers complete spatial coverage, and reduces the
761 amount of data that needs to be processed.

762 Coarse resolution data cannot be used directly to estimate area of forest change.
763 However, these data are useful for identifying locations of rapid change for further
764 analysis with higher resolution data or as an alert system for controlling deforestation
765 (see section on Brazilian national case study below). For example, MODIS data are used
766 as a stratification tool in combination with medium spatial resolution Landsat data to
767 estimate forest area cleared. The targeted sampling of change reduces the overall
768 resources typically required in assessing change over large nations. In cases where
769 clearings are large and/or change is rapid, visual interpretation or automated analysis
770 can be used to identify where change in forest area has occurred. Automated methods
771 such as mixture modeling and regression trees (Box 2.1.1) can also identify changes in
772 tree cover at the sub-pixel level. Validation of analyses with medium and high resolution
773 data in selected locations can be used to assess accuracy. The use of coarse resolution
774 data to identify deforestation hotspots is particularly useful to design a sampling strategy
775 (see following section).

776 **Box 2.1.1: Mixture models and regression trees**

777 Mixture models estimate the proportion of different land cover components within a
778 pixel. For example, each pixel is described as percentage vegetation, shade, and
779 bare soil components. Components sum to 100%. Image processing software
780 packages often provide mixture models using user-specified values for each end-
781 member (spectral values for pixels that contain 100% of each component).
782 Regression trees are another method to estimate proportions within each
783 component based on training data to calibrate the algorithm. Training data with
784 proportions of each component can be derived from higher resolution data. (see
785 Box 2.1.5 for more details)

786 **Utility of fine resolution data**

787 Fine resolution (< 5m) data, such as those collected from commercial sensors (e.g.,
788 IKONOS, QuickBird) and aircraft, can be prohibitively expensive to cover large areas.
789 However, these data can be used to calibrate algorithms for analyzing medium and high
790 resolution data and to verify the results — that is they can be used as a tool for “ground-
791 truthing” the interpretation of satellite imagery or for assessing the accuracy.

792

793 **2.1.2.4.4 Step 4: Decisions for sampling versus wall to wall coverage**

794 Wall-to-wall (an analysis that covers the full spatial extent of the forested areas) and
795 sampling approaches within the forest mask are both suitable methods for analyzing
796 forest area change.

797 The main criteria for the selection of wall-to-wall or sampling are:

798 Wall-to-wall is a common approach if appropriate for national circumstances

- 799 If resources are not sufficient to complete wall-to wall coverage, sampling is more
800 efficient, in particular for large countries
- 801 Recommended sampling approaches are systematic sampling and stratified
802 sampling (see box 2.1.2).

- 803 A sampling approach in one reporting period could be extended to wall-to-wall
804 coverage in the subsequent period.

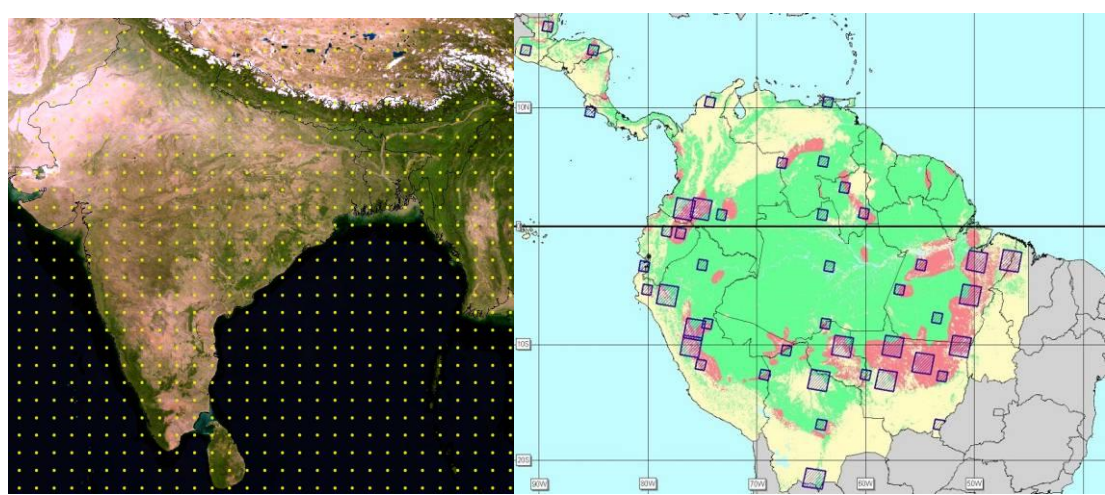
805 **Box 2.1.2: Systematic and stratified sampling**

806 Systematic sampling obtains samples on a regular interval, e.g. one every 10 km.

807 Sampling efficiency can be improved through spatial stratification ('stratified
808 sampling') using known proxy variables (e.g. deforestation hot spots). Proxy
809 variables can be derived from coarse resolution satellite data or by combining other
810 geo-referenced or map information such as distance to roads or settlements,
811 previous deforestation, or factors such as fires.

812 Example of systematic sampling

Example of stratified sampling



813
814 A stratified sampling approach for forest area change estimation is currently being
815 implemented within the NASA Land Cover and Land Use Change program. This
816 method relies on wall to wall MODIS change indicator maps (at 500 m resolution)
817 to stratify biomes into regions of varying change likelihood. A stratified sample of
818 Landsat-7 ETM+ image pairs is analyzed to quantify biome-wide area of forest
819 clearing. Change estimates can be derived at country level by adapting the sample
820 to the country territory.

821
822 A few very large countries, e.g. Brazil and India, have already demonstrated that
823 operational wall to wall systems can be established based on mid-resolution satellite
824 imagery (see section 3.2 for further details). Brazil has measured deforestation rates in
825 Brazilian Amazonia since the 1980s. These methods could be easily adapted to cope with
826 smaller country sizes. Although a wall-to-wall coverage is ideal, it may not be practical
827 due to large areas and constraints on resources for accurate analysis.

828 **2.1.2.4.5 Step 5: Process and analyze the satellite data**

829 **Step 5.1: Preprocessing**

830 Satellite imagery usually goes through three main pre-processing steps: geometric
831 corrections are needed to ensure that images in a time series overlay properly, cloud
832 removal is usually the second step in image pre-processing and radiometric corrections
833 are recommended to make change interpretation easier (by ensuring that images have
834 the same spectral values for the same objects).

- 835 Geometric corrections
- 836 • Low geolocation error of change datasets is to be ensured: average
837 geolocation error (relative between 2 images) should be < 1 pixel

- 838 • Existing Landsat Geocover data usually provide sufficient geometric accuracy
- 839 and can be used as a baseline; for limited areas Landsat Geocover has
- 840 geolocation problems
- 841 • Using additional data like non-Geocover Landsat, SPOT, etc. requires effort in
- 842 manual or automated georectification using ground control points or image to
- 843 image registration.
- 844 Cloud and cloud shadow detection and removal
- 845 • Visual interpretation is the preferred method for areas without complete
- 846 cloud-free satellite coverage,
- 847 • Clouds and cloud shadows to be removed for automated approaches
- 848 Radiometric corrections
- 849 • Effort needed for radiometric corrections depends on the change assessment
- 850 approach
- 851 • For simple scene by scene analysis (e.g. visual interpretation), the radiometric
- 852 effects of topography and atmosphere should be considered in the
- 853 interpretation process but do not need to be digitally normalized)
- 854 • Sophisticated digital and automated approaches may require radiometric
- 855 correction to calibrate spectral values to the same reference objects in
- 856 multitemporal datasets. This is usually done by identifying a water body or
- 857 dark object and calibrating the other images to the first.
- 858 • Reduction of haze maybe a useful complementary option for digital
- 859 approaches. The image contamination by haze is relatively frequent in tropical
- 860 regions. Therefore, when no alternative imagery is available, the correction of
- 861 haze is recommended before image analysis. Partially haze contaminated
- 862 images can be corrected through a tasseled cap transformation¹⁶.
- 863 • Topographic normalization is recommended for mountainous environments
- 864 from a digital terrain model (DTM). For medium resolution data the SRTM
- 865 (shuttle radar topography mission) DTM can be used with automated
- 866 approaches¹⁷

867 **Step 5.2: Analysis methods**

868 Many methods exist to interpret images (Table 2.1.3). The selection of the method
 869 depends on available resources and whether image processing software is available.
 870 Whichever method is selected, the results should be repeatable by different analysts.

871 It is generally more difficult to identify reforestation than deforestation. Reforestation
 872 occurs gradually over a number of years while deforestation occurs more rapidly.
 873 Deforestation is therefore more visible. Higher resolution, additional field work, and
 874 accuracy assessment may be required if reforestation as well as deforestation need to be
 875 monitored.

876 Visual scene to scene interpretation of forest area change can be simple and robust,
 877 although it is a time-consuming method. A combination of automated methods
 878 (segmentation or classification) and visual interpretation can reduce the work load.
 879 Automated methods are generally preferable where possible because the interpretation
 880 is repeatable and efficient. Even in a fully automated process, visual inspection of the

¹⁶ Lavreau J. 1991. De-hazing Landsat Thematic Mapper images, *Photogrammetric Engineering & Remote Sensing*, 57:1297–1302.

¹⁷ E.g. Gallaun H, Schardt M & Linser S (2007) Remote sensing based forest map of Austria and derived environmental indicators. ForestSAT 2007 Conference, Montpellier, France.

881 result by an analyst familiar with the region should be carried out to ensure appropriate
882 interpretation.

883 A preliminary visual screening of the image pairs can serve to identify the sample sites
884 where change has occurred between the two dates. This data stratification allows
885 removing the image pairs without change from the processing chain (for the detection
886 and measurement of change).

887 Changes (for each image pair) can then be measured by comparing the two multi-date
888 final forest maps. The timing of image pairs has to be adjusted to the reference period,
889 e.g. if selected images are dated 1999 and 2006, it would have to be adjusted to 2000-
890 2005.

891 **Visual delineation of land entities:**

892 This approach is viable, particularly if image analysis tools and experiences are limited.
893 The visual delineation of land entities on printouts (used in former times) is not
894 recommended. On screen delineation should be preferred as producing directly digital
895 results. When land entities are delineated visually, they should also be labeled visually.

896 **Table 2.1.3: Main analysis methods for moderate resolution (~ 30 m) imagery**

Method for delineation	Method for class labeling	Practical minimum mapping unit	Principles for use	Advantages / limitations
Dot interpretation (dots sample)	Visual interpretation	< 0.1 ha	- multiple date preferable to single date interpretation - On screen preferable to printouts interpretation	- closest to classical forestry inventories - very accurate although interpreter dependent - no map of changes
Visual delineation (full image)	Visual interpretation	5 – 10 ha	- multiple date analysis preferable - On screen digitizing preferable to delineation on printouts	- easy to implement - time consuming - interpreter dependent
Pixel based classification	Supervised labeling (with training and correction phases)	<1 ha	- selection of common spectral training set from multiple dates / images preferable - filtering needed to avoid noise	- difficult to implement - training phase needed
	Unsupervised clustering + Visual labeling	<1 ha	- interdependent (multiple date) labeling preferable - filtering needed to avoid noise	- difficult to implement - noisy effect without filtering
Object based segmentation	Supervised labeling (with training and correction phases)	1 - 5 ha	- multiple date segmentation preferable - selection of common spectral training set from multiple dates / images preferable	- more reproducible than visual delineation - training phase needed
	Unsupervised clustering + Visual labeling	1 - 5 ha	- multiple date segmentation preferable - interdependent (multiple date) labeling of single date images preferable	- more reproducible than visual delineation

897

898 **Multi-date image segmentation:**

899 Segmentation for delineating image objects reduces the processing time of image
900 analysis. The delineation provided by this approach is not only more rapid and automatic

901 but also finer than what could be achieved using a manual approach. It is repeatable and
902 therefore more objective than a visual delineation by an analyst. Using multi-date
903 segmentations rather than a pair of individual segmentations is justified by the final
904 objective which is to determine change.

905 If a segmentation approach is used, the image processing can be ideally decomposed
906 into four steps:

- 907 I. Multi-date image segmentation is applied on image pairs: groups of adjacent
908 pixels that show similar area change trajectories between the 2 dates are
909 delineated into objects.
- 910 II. Training areas are selected for all land classes in each of the 2 dates (in the
911 case of more than one image pair and if all images are radiometrically
912 corrected, this step can be prepared initially by selecting a set of representative
913 spectral signatures for each class – as average from different training areas)
- 914 III. Objects from every extract (i.e. every date) are classified separately by
915 supervised clustering procedures, leading to two automated forest maps (at
916 date 1 and date 2)
- 917 IV. Visual interpretation is conducted interdependently on the image pairs to
918 verify/adjust the label of the classes and edit possible automatic classification
919 errors.

Image segmentation is the process of partitioning an image into groups of pixels that are spectrally similar and spatially adjacent. Boundaries of pixel groups delineate ground objects in much the same way a human analyst would do based on its shape, tone and texture. However, delineation is more accurate and objective since it is carried out at the pixel level based on quantitative values

920

921

922 **Digital classification techniques:**

923 Digital classification into clusters applies in the case of automatic delineation of
924 segments.

925 After segmentation, it is recommended to apply two supervised object classifications
926 separately on the two multi-date images instead of applying a single supervised object
927 classification on the image pair because two separate land classifications are much easier
928 to produce in a supervised step than a direct classification of change trajectories.

929 The supervised object classification should ideally use a common predefined standard
930 training data set of spectral signatures for each type of ecosystem to create initial
931 automated forest maps (at any date and any location within this ecosystem).

932 Although unsupervised clustering (followed by visual labeling) is also possible, for large
933 areas (i.e. for more than a few satellite images) it is recommended to apply supervised
934 object classification (with a training phase beforehand and a labeling
935 correction/validation phase afterwards). An unsupervised direct classification of change
936 trajectories of the 2 multivariate images together implies a second step of visual labeling of
937 the classification result into the different combination of change classes which is a time-
938 consuming task. The multivariate segmentation followed by supervised classification of
939 individual dates is considered more efficient in the case of a large number of images.
940 Other methodological options (see [Table 2.1.3](#)) can be used depending on the specific
941 conditions or expertise within a country.

942

943 **General recommendations for image object interpretation methods:**

944 Given the heterogeneity of the forest spectral signatures and the occasionally poor
945 radiometric conditions, the image analysis by a skilled interpreter is indispensable to
946 map land use and land use change with high accuracy.

947 Interpretation should focus on change in land use with interdependent visual
948 assessment of 2 multi-temporal images together. Contrarily to digital
949 classification techniques, visual interpretation is easier with multi-temporal
950 imagery.

951 Existing maps may be useful for stratification or helping in the interpretation

952 Scene by scene (i.e. site by site) interpretation is more accurate than
953 interpretation of scene or image mosaics

954 Spectral, spatial and temporal (seasonality) characteristics of the forests have to
955 be considered during the interpretation. In the case of seasonal forests, scenes
956 from the same time of year should be used. Preferably, multiple scenes from
957 different seasons would be used to ensure that changes in forest cover from
958 inter-annual variability in climate are not confused with deforestation.

959

960 **2.1.2.4.6 Step 6: Accuracy assessment**

961 An independent accuracy assessment is an essential component to link area estimates to
962 a crediting system. Reporting accuracy and verification of results are essential
963 components of a monitoring system. Accuracy could be quantified following
964 recommendations of chapter 5 of IPCC Good Practice Guidance 2003.

965 Accuracies of 80 to 95% are achievable for monitoring with mid-resolution imagery to
966 discriminate between forest and non-forest. Accuracies can be assessed through *in-situ*
967 observations or analysis of very high resolution aircraft or satellite data. In both cases, a
968 statistically valid sampling procedure should be used to determine accuracy.

969 A detailed description of methods to be used for accuracy assessment is provided in
970 section 2.6 ("Estimating uncertainties in area estimates").

971 **2.1.3 Monitoring of forest area changes within forests - forest land**
972 **remaining forest land**

973

974 Many activities cause degradation of carbon stocks within forests but not all of them can
975 be monitored well with high certainty using remote sensing data. As discussed above in
976 Section 1.2.2, the gaps in the canopy caused by selective harvesting of trees (both legal
977 and illegal) can be detected in imagery such as Landsat using sophisticated analytical
978 techniques of frequently collected imagery, and the task is somewhat easier when the
979 logging activity is more intense (i.e. higher number of trees logged). Higher intensity
980 logging is likely to cause more change in canopy characteristics, and thus an increased
981 chance that this could be monitored with Landsat type imagery and interpretation. The
982 area of forests undergoing selective logging can also be interpreted in remote sensing
983 imagery based on the observations of networks of roads and log decks that are often
984 clearly recognizable in the imagery.

985 Degradation of carbon stocks by forest fires is usually easier to identify and monitor with
986 existing satellite imagery than logging. Degradation from fires is also important for
987 carbon fluxes. The trajectory of spectral responses on satellite imagery over time is
988 useful for tracking burned area.

989 Degradation by over exploitation for fuel wood or other local uses of wood often followed
990 by animal grazing that prevents regeneration, a situation more common in drier forest

991 areas, is likely not to be detectable from satellite image interpretation unless the rate of
992 degradation was intense causing larger changes in the canopy and thus monitoring
993 methods are not presented here.

994 In this section, two approaches are presented that could be used to monitor logging: the
995 direct approach that detects gaps and the indirect approach that detects road networks
996 and log decks. (The timber harvesting forestry practice that fells all the trees, commonly
997 referred to as clear cutting, is also considered to be degradation if it results in a net
998 decrease of carbon stocks over a period of X years on a large area).

999

1000

Key Definitions

1001 **Intact forest:** patches of forest that are not damaged or surrounded by small clearings;
1002 forests without gaps caused by human activities.

1003 **Forest canopy gaps:** In logged areas, canopy gaps are created by tree fall and skid
1004 trails, resulting in damage or death of standing trees.

1005 **Log landings:** a more severe type of damage caused when the forest is cleared for the
1006 purposes of temporary timber storage and handling; bare soil is often exposed.

1007 **Logging roads:** roads built to transport timber from log landings to sawmills – their
1008 width varies by country from about 3 m to as much as 15 m.

1009 **Regeneration:** forests recovering from previous damage, resulting in carbon
1010 sequestration.

1011

2.1.3.1 Direct approach to monitor selective logging

1013 Mapping forest degradation with remote sensing data is more challenging than mapping
1014 deforestation because the degraded forest is a complex mix of different land cover types
1015 (vegetation, dead trees, soil, shade) and the spectral signature of the degradation
1016 changes quickly (i.e., < 2 years). High spatial resolution sensors such as Landsat, ASTER
1017 and SPOT have been mostly used so far to address this issue. However, very high
1018 resolution satellite imagery, such as Ikonos or Quickbird, and aerial digital image
1019 acquired with videography have been used as well. Here, the methods available to detect
1020 and map forest degradation caused by selective logging and forest fires – the most
1021 predominant types of degradation in tropical regions – using optical sensors only are
1022 presented.

1023 Methods for mapping forest degradation range from simple image interpretation to
1024 highly sophisticated automated algorithms. Because the focus is on estimating forest
1025 carbon losses associated with degradation, forest canopy gaps and small clearings are
1026 the feature of interest to be enhanced and extracted from the satellite imagery. In the
1027 case of logging, the damage is associated with areas of tree fall gaps, clearings
1028 associated with roads and log landings (i.e., areas cleared to store harvested timber
1029 temporarily), and skid trails. The forest canopy gaps and clearings are intermixed with
1030 patches of undamaged forests (Figure 2.1.1).

1031

1032 **Figure 2.1.1:** Very high resolution Ikonos image showing common features in
 1033 selectively logged forests in the Eastern Brazilian Amazon



(image size: 11 km x 11 km)

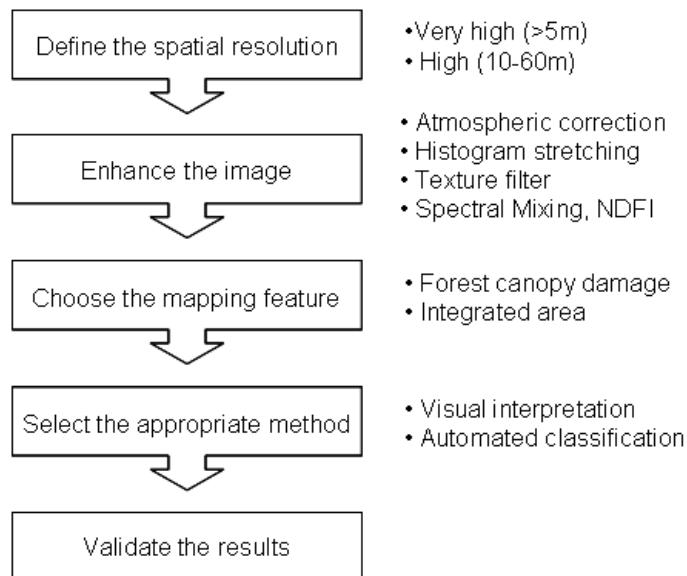
1034

1035

1036 There are two possible methodological approaches to map logged areas: 1) identifying
 1037 and mapping forest canopy damage (gaps and clearings); or 2) mapping the combined,
 1038 i.e., integrated, area of forest canopy damage, intact forest and regeneration patches.
 1039 Estimating the proportion of forest carbon loss in the latter mapping approach is more
 1040 challenging requiring field sampling measurements of forest canopy damage and
 1041 extrapolation to the whole integrated area to estimate the damage proportion (see
 1042 section 2.5).

1043 Mapping forest degradation associated with fires is simpler than that associated with
 1044 logging because the degraded environment is usually contiguous and more
 1045 homogeneous than logged areas. Moreover, the associated carbon emissions may be
 1046 higher than for selective logging.

1047 The following chart illustrates the steps needed to map forest degradation:



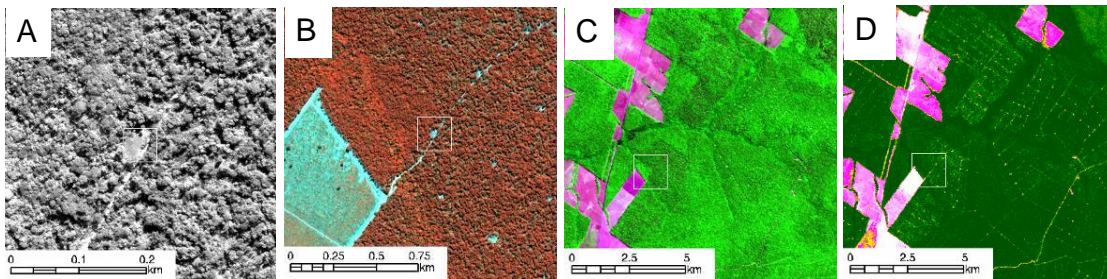
1048

1049 In this chart "Very high (>5m)" should read as "Fine (<5m)" and "High (10-60m)" as "Medium
 1050 (10-60m)" (refer to Table 2.1.1)

1051 **2.1.3.1.1 Step 1: Define the spatial resolution**

1052 Defining the appropriate spatial resolution to map forest degradation due to selective
1053 logging depends on the type of harvesting operation (managed or unplanned). Certain
1054 non-mechanized logging practiced in a few areas of e.g., the Brazilian Amazon, cannot
1055 be detected using spatial resolution in the order of 30-60 m (Figure 2.1.2) because these
1056 type of logging create small forest gaps and little damage to the canopy. In addition,
1057 logging of floodplain ("varzea") forests is very difficult to map because waterways are
1058 used in place of skid trails and logging roads. Very high resolution imagery, as acquired
1059 with orbital and aerial digital videography, is required to directly map forest canopy
1060 damage of these types. Unplanned logging generally creates more impact allowing the
1061 detection of forest canopy damage at spatial resolution between 30-60 m.

1062 **Figure 2.1.2. Unplanned logged forest in Sinop, Mato Grosso, Brazilian Amazon**
1063 in: (A) Ikonos panchromatic image (1 meter pixel); (B) Ikonos multi-spectral and
1064 panchromatic fusion (4 meter pixel); (C) Landsat TM5 multi-spectral (R5, G4, B3; 30
1065 meter pixel); and (D) Normalized Difference Fraction Index (NDFI) image (sub-pixel
1066 within 30 m). These images were acquired in August 2001.



1068 **2.1.3.1.2 Step 2: Enhance the image**

1069 Detecting forest degradation with satellite images usually requires improving the spectral
1070 contrast of the degradation signature relative to the background. In tropical forest
1071 regions, atmospheric correction and haze removal are recommended techniques to be
1072 applied to high resolution images. Histogram stretching improves image color contrast
1073 and is a recommended technique. However, at high spatial resolution histogram
1074 stretching is not enough to enhance the image to detect forest degradation due to
1075 logging. Figure 2.1.2C shows an example of a color composite of reflectance bands
1076 (R5,G4,B3) of Landsat image after a linear stretching with little or no evidence of
1077 logging. At fine/moderate spatial resolution, such as the resolution of Landsat and Spot 4
1078 images, a spectral mixed signal of green vegetation (GV; also often called PV or
1079 photosynthetic vegetation), soil, non-photosynthetic vegetation (NPV) and shade is
1080 expected within the pixels. That is why the most robust techniques to map selective
1081 logging impacts are based on fraction images derived from spectral mixture analysis
1082 (SMA). Fractions are sub-pixel estimates of the pure materials (endmembers) expected
1083 within pixel sizes such as those of Landsat (i.e., 30 m): GV, soil, NPV and shade
1084 endmembers (see SMA Box 1). Figure 2.1.2D shows the same area and image as Figure
1085 2.1.2C with logging signature enhanced with the Normalized Difference Fraction Index
1086 (NDFI; see Box 3.5). The SMA and NDFI have been successfully applied to Landsat and
1087 SPOT images in the Brazilian Amazon to enhance the detection of logging and burned
1088 forests (Figure 2.1.3).

1089 Because the degradation signatures of logging and forest fires change quickly in high
1090 resolution imagery (i.e., < one year), annual mapping is required. Figure 2.1.3 illustrates
1091 this problem showing logging and forest fires scars changing every year over the period
1092 of 1998 to 2003. This has important implications for estimating emissions from
1093 degradation because old degraded forests (i.e., with less carbon stocks) can be
1094 misclassified as intact forests. Therefore, annual detection and mapping the areas with
1095 canopy damage associated with logging and forest fires is mandatory to monitoring
1096 forest degradation with high resolution multispectral imagery such as SPOT and Landsat.

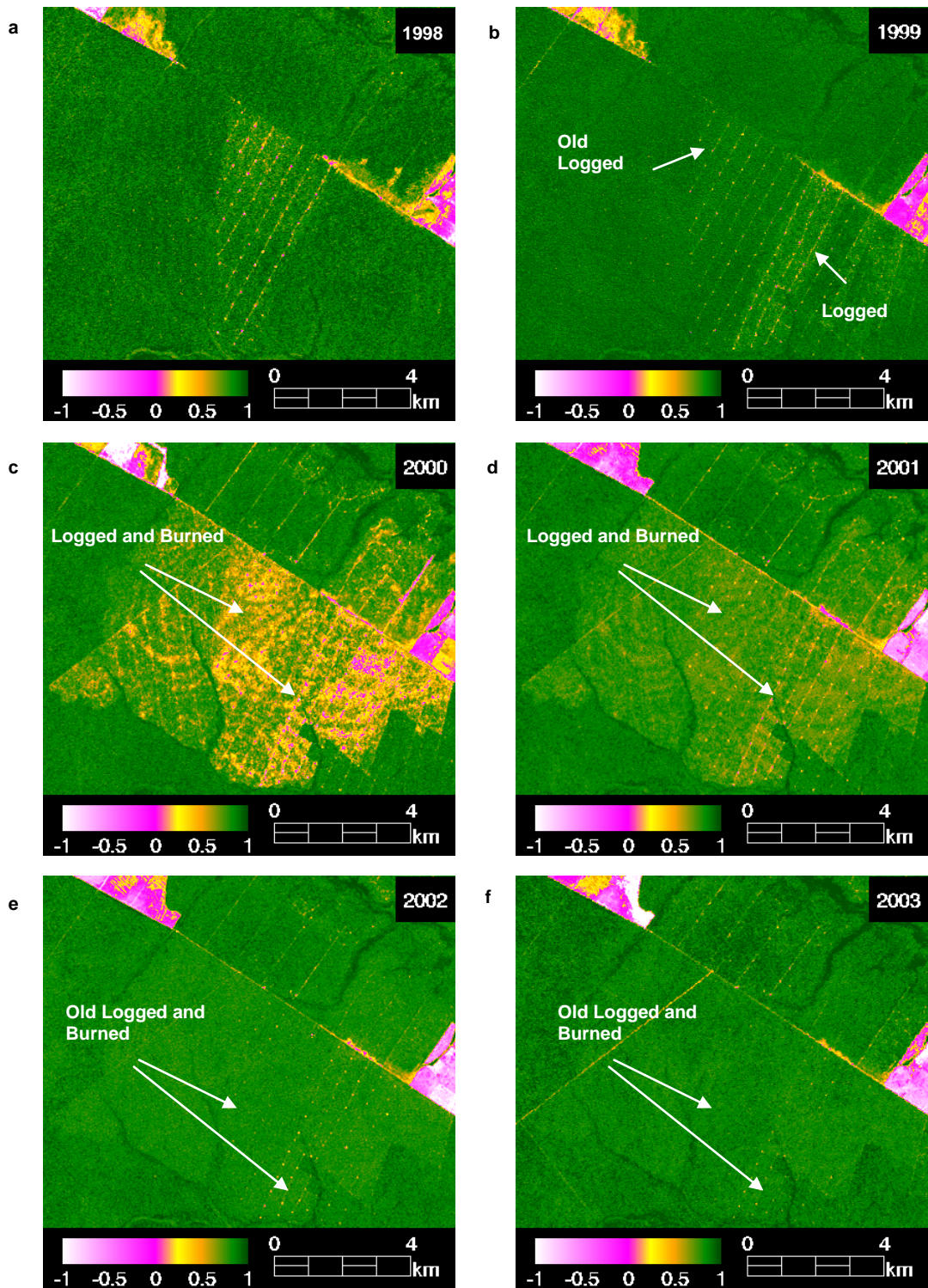
1097

1098

1099

1100

Figure 2.1.3: Forest degradation annual change due to selective logging and logging and burning in Sinop region, Mato Grosso State, Brazil.



1101

1102 **Step 3: Select the mapping feature and methods**

1103 Forest canopy damage (gaps and clearings) areas are easier to identify in very high
1104 spatial resolution images (Figure 2.1.2.A-B). Image visual interpretation or automated
1105 image segmentation can be used to map forest canopy damage areas at this resolution.
1106 However, there is a tradeoff between these two methodological approaches when applied
1107 to the very high spatial resolution images. Visual identification and delineation of canopy
1108 damage and small clearings are more accurate but time consuming, whereas automated
1109 segmentation is faster but generates false positive errors that usually require visual
1110 auditing and manual correction of these errors. High spatial resolution imagery is the
1111 most common type of images used to map logging (unplanned) over large areas. Visual
1112 interpretation at this resolution does not allow the interpreter to identify individual gaps
1113 and because of this limitation the integrated area – including forest canopy damage, and
1114 patches of intact forest and regeneration – is the chosen mapping feature with this
1115 approach. Most of the automated techniques – applied at high spatial resolution – map
1116 the integrated area as well with only the ones based on image segmentation and change
1117 detection able to map directly forest canopy damage. In the case of burned forests, both
1118 visual interpretation and automated algorithms can be used and very high and high
1119 spatial resolution imagery have been used.

1120 **Data Needs**

1121 There are several optical sensors that can be used to map forest degradation caused by
1122 selective logging and forest fires (Table 2.1.5). Users might consider the following
1123 factors when defining data needs:

- 1124 Degradation intensity—is the logging intensity low or high?
- 1125 Extent of the area for analysis—large or small areal extent?
- 1126 Technique that will be used—visual or automated?

1127 Very high spatial resolution sensors will be required for mapping low intensity
1128 degradation. Small areas can be mapped at this resolution as well if cost is not a limiting
1129 factor. If degradation intensity is low and area is large, indirect methods are preferred
1130 because cost for acquisition of very high resolution imagery may be prohibitive (see
1131 section on Indirect Methods to Map Forest Degradation). For very large areas, high
1132 spatial resolution sensors produce satisfactory estimates of the area affected by
1133 degradation.

1134 The spectral resolution and quality of the radiometric signal must be taken into account
1135 for monitoring forest degradation at high spatial resolution. The estimation of the
1136 abundance of the materials (i.e., end-members) found with the forested pixels, through
1137 SMA, requires at least four spectral bands placed in spectral regions that contrast the
1138 end-members spectral signatures (see Box 2.1.5).

1139

1140

1141 **Table 2.1.5: Remote sensing methods tested and validated to map forest**
 1142 **degradation caused by selective logging and burning in the Brazilian Amazon.**

1143

1144

Mapping Approach	Sensor	Spatial Extent	Objective	Advantages	Disadvantages
Visual Interpretation	Landsat TM5	Local and Brazilian Amazon	Map integrated logging area and canopy damage of burned forest	Does not require sophisticated image processing techniques	Labor intensive for large areas and may be user biased to define the boundaries of the degraded forest.
Detection of Logging Landings + Harvesting Buffer	Landsat TM5 and ETM+	Local	Map integrated logging area	Relatively simple to implement and satisfactorily estimate the area	Harvesting buffers varies across the landscape and does not reproduce the actual shape of the logged area
Decision Tree	SPOT 4	Local	Map forest canopy damage associated with logging and burning	Simple and intuitive binary classification rules, defined automatically based on statistical methods	It has not been tested in very large areas and classification rules may vary across the landscape
Change Detection	Landsat TM5 and ETM+	Local	Map forest canopy damage associated with logging and burning	Enhances forest canopy damaged areas.	Requires two pairs of radiometrically calibrated images and does not separate natural and anthropogenic forest changes
Image Segmentation	Landsat TM5	Local	Map integrated logged area	Relatively simple to implement	Not been tested in very large areas. segmentation rules may vary across the landscape
Textural Filters	Landsat TM5 and ETM+	Brazilian Amazon	Map forest canopy damage associated	Relatively simple to implement	
CLAS ¹⁸	Landsat TM5 and ETM+	Three states of the Brazilian Amazon (PA, MT and AC)	Map total logging area (canopy damage, clearings and undamaged forest)	Fully automated and standardized to very large areas.	Requires very high computation power, and pairs of images to detect forest change associated with logging. Requires additional image types for atmospheric correction (MODIS)
CLASlite ¹⁹	Landsat TM, ETM+ ASTER, ALI, SPOT MODIS,	Regional, anywhere that imagery exists	Rapid mapping of deforestation and degradation at sub-national scales	Fully automated, uses a standard computer, requires no expertise	Creates basic forest cover maps but does not do final classification of land uses
NDFI+CCA ²⁰	Landsat TM5 and ETM+	Local	Map forest canopy damage associated with logging and burning	Enhances forest canopy damaged areas.	It has not been tested in very large areas and does not separate logging from burning

¹⁸ CLAS: Carnegie Landsat Analysis System

¹⁹ <http://claslite.ciw.edu>

²⁰ NDFI: Normalized Difference Fraction Index; CCA: Contextual Classification Algorithm

Box 2.1.5: Spectral Mixture Analysis (SMA)

Detection and mapping forest degradation with remotely sensed data is more challenging than mapping forest conversion because the degraded forest is a complex environment with a mixture of different land cover types (i.e., vegetation, dead trees, bark, soil, shade), causing a mixed pixel problem (see Figure 2.1.3). In degraded forest environments, the reflectance of each pixel can be decomposed into fractions of green vegetation (GV), non-photosynthetic vegetation (NPV; e.g., dead tree and bark), soil and shade through Spectral Mixture Analysis (SMA). The output of SMA models are fraction images of each pure material found within the degraded forest pixel, known as endmembers. Fractions are more intuitive to interpret than the reflectance of mixed pixels (most common signature at high spatial resolution). For example, soil fraction enhances log landings and logging roads; NPV fraction enhances forest damage and the GV fraction is sensitive to canopy gaps.

The SMA model assumes that the image spectra are formed by a linear combination of n pure spectra [or endmembers], such that:

$$(1) \quad R_b = \sum_{i=1}^n F_i \cdot R_{i,b} + \varepsilon_b$$

for

$$(2) \quad \sum_{i=1}^n F_i = 1$$

where R_b is the reflectance in band b , $R_{i,b}$ is the reflectance for endmember i , in band b , F_i the fraction of endmember i , and ε_b is the residual error for each band. The SMA model error is estimated for each image pixel by computing the RMS error, given by:

$$(3) \quad RMS = \left[n^{-1} \sum_{b=1}^n \varepsilon_b^2 \right]^{1/2}$$

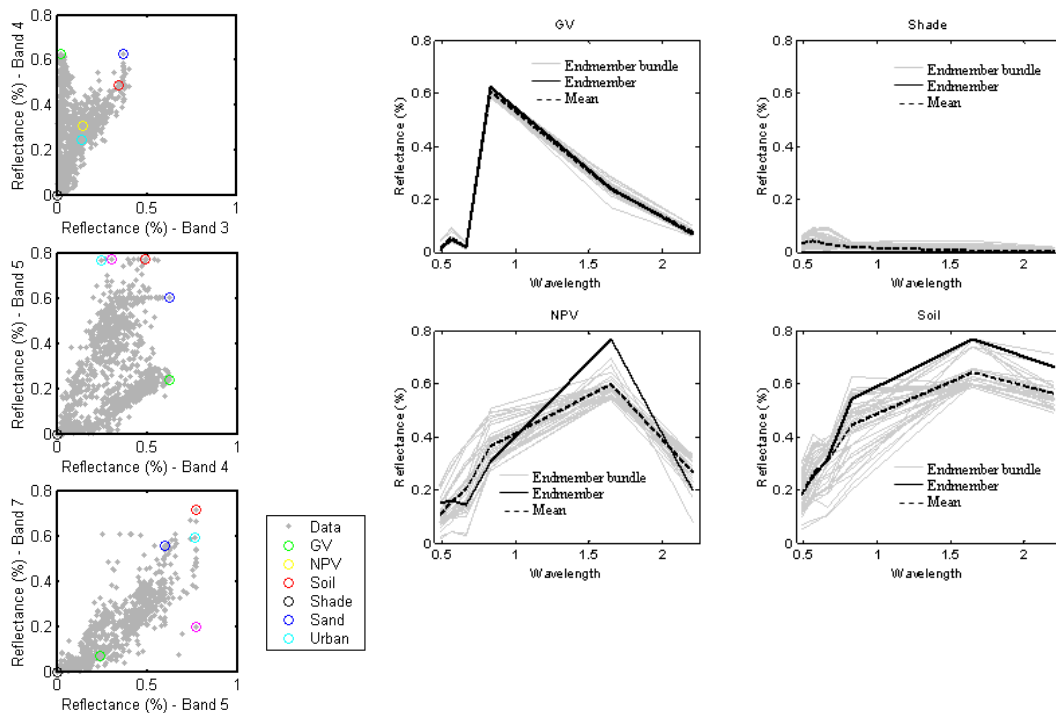
The identification of the nature and number of pure spectra (i.e., endmembers), in the image scene is the most important step for a successful application of SMA models. In Landsat TM/ETM+ images the four types of endmembers are expected in degraded forest environments (GV, NPV, Soil and Shade) can be easily identified in the extreme of image bands scatterplots.

The pixels located at the extremes of the data cloud of the Landsat spectral space are candidate endmembers to run SMA. The final endmembers are selected based on the spectral shape and image context (e.g., soil spectra are mostly associated with unpaved roads and NPV with pasture having senesced vegetation) (figure below).

The SMA model results were evaluated as follows: (1) fraction images are evaluated and interpreted in terms of field context and spatial distribution; (2) the histograms of the fraction images are inspected to evaluate if the models produced physically meaningful results (i.e., fractions ranging from zero to 100%). In time-series applications, as required to monitor forest degradation, fraction values must be consistent over time for invariant targets (i.e., that intact forest not subject to phenological changes must have similar values over time). Several image processing software have spectral plotting and SMA functionalities.

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Box 2.1.5: Continuation



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Image scatter-plots of Landsat bands in reflectance space and the spectral curves of GV, Shade, NPV and Soil.

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Limitations for forest degradation

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There are limiting factors to all methods described above that might be taken into consideration when mapping forest degradation. First, it requires frequent mapping, at least annually, because the spatial signatures of the degraded forests change after one year. Additionally, it is important to keep track of repeated degradation events that affect more drastically the forest structure and composition resulting in greater changes in carbon stocks. Second, the human-caused forest degradation signal can be confused with natural forest changes such as wind throws and seasonal changes. Confusion due to seasonality can be reduced by using more frequent satellite observations. Third, all the methods described above are based on optical sensors which are limited by frequent cloud conditions in tropical regions. Finally, higher level of expertise is required to use the most robust automated techniques requiring specialized software and investments in capacity building.

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Box 2.1.6: Calculating Normalized Difference Fraction Index (NDFI)

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The detection of logging impacts at moderate spatial resolution is best accomplished at the subpixel scale, with spectral mixture analysis (SMA). Fraction images obtained with SMA can enhance the detection of logging infrastructure and canopy damage. For example, soil fraction can enhance the detection of logging decks and logging roads; NPV fraction enhances damaged and dead vegetation and green vegetation the canopy openings. A new spectral index obtained from fractions derived from SMA, the Normalized Difference Fraction Index (NDFI), enhances even more the degradation signal caused by selective logging. The NDFI is computed by:

1217 (1)
$$NDFI = \frac{GV_{Shade} - (NPV + Soil)}{GV_{Shade} + NPV + Soil}$$

1218 where GVshade is the shade-normalized GV fraction given by:

1219 (2)
$$GV_{Shade} = \frac{GV}{100 - Shade}$$

1220 The NDFI values range from -1 to 1. For intact forest NDFI values are expected to
1221 be high (i.e., about 1) due to the combination of high GVshade (i.e., high GV and
1222 canopy Shade) and low NPV and Soil values. As forest becomes degraded, the NPV
1223 and Soil fractions are expected to increase, lowering the NDFI values relative to
1224 intact forest.

1225 **Special software requirements and costs**

1226 All the techniques described in this section are available in most remote sensing,
1227 commercial and public domain software. The software must have the capability to
1228 generate GIS vector layers in case image interpretation is chosen, and being able to
1229 perform SMA for image enhancement. Image segmentation is the most sophisticated
1230 routine required, being available in a few commercial and public domain software
1231 packages. Additionally, it is desired that the software allows adding new functions to be
1232 added to implement new specialized routines, and have script capability to batch mode
1233 processing of large volume of image data.

1234 **Progress in developments of national monitoring systems**

1235 All the techniques discussed in this section (Direct approach to monitor selective logging)
1236 were developed and validated in the Brazilian Amazon. Recent efforts to export these
1237 methodologies to other areas are underway. For example, SMA and NDFI have being
1238 tested in Bolivia with Landsat and Aster imagery. The preliminary results showed that
1239 forest canopy damage of low intensity logging, the most common type of logging in the
1240 region, could not be detected with Landsat. This corroborates with the findings in the
1241 Brazilian Amazon. New sensor data with higher spatial resolution are currently being
1242 tested in Bolivia, including Spot 5 (10 m) and Aster (15 m) to evaluate the best sensor
1243 for their operational system. Given their higher spatial resolution, Aster and Spot
1244 imagery are showing promise for detecting and mapping low intensity logging in Bolivia.

1245

1246 **2.1.3.2 Indirect approach to monitor forest degradation**

1247 Often a direct remote sensing approach to assess forest degradation can not be adopted
1248 for various limiting factors (see previous section) which are even more restrictive if
1249 forest degradation has to be measured for a historical period and thus observed only
1250 with remote sensing data that are already available in the archives.

1251 Moreover the forest definition contained in the UNFCCC framework of provisions
1252 (UNFCCC, 2001) does not discriminate between forests with different carbon stocks, and
1253 often forest land subcategories defined by countries are based on concepts related to
1254 different forest types (e.g. species compositions) or ecosystems than can be delineated
1255 through remote sensing data or through geo-spatial criteria (e.g. altitude).
1256 Consequently, any accounting system based on forest definitions that are not containing
1257 parameters related to carbon content, will require an extensive and high intensive
1258 carbon stock measuring effort (e.g. national forest inventory) in order to report on
1259 emissions from forest degradation.

1260 In this context, i.e. the need for activity data (area changes) on degraded forest under
1261 the UNFCCC reporting requirement and the lack of remote sensing data for an
1262 exhaustive monitoring system, a new methodology has been elaborated with the aim of

1263 providing an operational tool that could be applied worldwide. This methodology consists
1264 mainly in the adaptation of the concepts and criteria already developed to assess the
1265 world's intact forest landscape in the framework of the IPCC Guidance and Guidelines to
1266 report GHG emission from forest land. In this new context, the intact forest concept has
1267 been used as a proxy to identify forest land without anthropogenic disturbance so as to
1268 assess the carbon content present in the forest land:

- 1269 intact forests: fully-stocked (any forest with tree cover between 10% and 100%
1270 but must be undisturbed, i.e. there has been no timber extraction)
- 1271 non-intact forests: not fully-stocked (tree cover must still be higher than 10% to
1272 qualify as a forest under the existing UNFCCC rules, but in our definition we
1273 assume that in the forest has undergone some level of timber exploitation or
1274 canopy degradation).

1275 This distinction should be applied in any forest land use subcategories (forest
1276 stratification) that a country is aiming to report under UNFCCC. So for example, if a
1277 country is reporting emissions from its forest land using two forest land subcategories,
1278 e.g. lowland forest and mountain forest, it should further stratify its territory using the
1279 intact approach and in this way it will report on four forest land sub-categories: intact
1280 lowland forest; non-intact lowland forest, intact mountain forest and non-intact
1281 mountain forest. Thus a country will also have to collect the corresponding carbon pools
1282 data in order to characterize each forest land subcategories.

1283 The intact forest areas are defined according to parameters based on spatial criteria that
1284 could be applied objectively and systematically over all the country territory. Each
1285 country according to its specific national circumstance (e.g. forest practices) may
1286 develop its intact forest definition. Here we suggest an intact forest area definition based
1287 on the following six criteria:

- 1288 Situated within the forest land according to current UNFCCC definitions and with a
1289 1 km buffer zone inside the forest area;
- 1290 Larger than 1,000 hectares and with a smallest width of 1 kilometers;
- 1291 Containing a contiguous mosaic of natural ecosystems;
- 1292 Not fragmented by infrastructure (road, navigable river, pipeline, etc.);
- 1293 Without signs of significant human transformation;
- 1294 Without burnt lands and young tree sites adjacent to infrastructure objects.

1295 These criteria with larger thresholds for minimum area extension and buffer distance
1296 have been used to map intact forest areas globally (www.intactforests.org).

1297 These criteria can be adapted at the country or ecosystem level. For example the
1298 minimum extension of an intact forest area or the minimum width can be reduced for
1299 mangrove ecosystems. It must be noted that by using these criteria a non-intact forest
1300 area would remain non-intact for long time even after the end of human activities, until
1301 the signs of human transformation would disappear.

1302 The adoption of the 'intact' concept is also driven by technical and practical reasons. In
1303 compliance with current UNFCCC practice it is the Parties' responsibilities to identify
1304 forests according to the established 10% - 100% cover range rule. When assessing the
1305 condition of such forest areas using satellite remote sensing methodologies, the
1306 "negative approach" can be used to discriminate between intact and non-intact forests:
1307 disturbance such as the development of roads can be easily detected, whilst the absence
1308 of such visual evidence of disturbance can be taken as evidence that what is left is
1309 intact. Disturbance is easier to unequivocally identify from satellite imagery than the
1310 forest ecosystem characteristics which would need to be determined if we followed the
1311 "positive approach" i.e. identifying intact forest and then determining that the rest is
1312 non-intact. Following this approach forest conversions between intact forests, non-intact
1313 forests and other land uses can be easily measured worldwide through Earth observation

1314 satellite imagery; in contrast, any other forest definition (e.g. pristine, virgin,
1315 primary/secondary, etc...) is not always measurable.

1316 **Method for delineation of intact forest landscapes**

1317 A two-step procedure could be used to exclude non-intact areas and delineate the
1318 remaining intact forest:

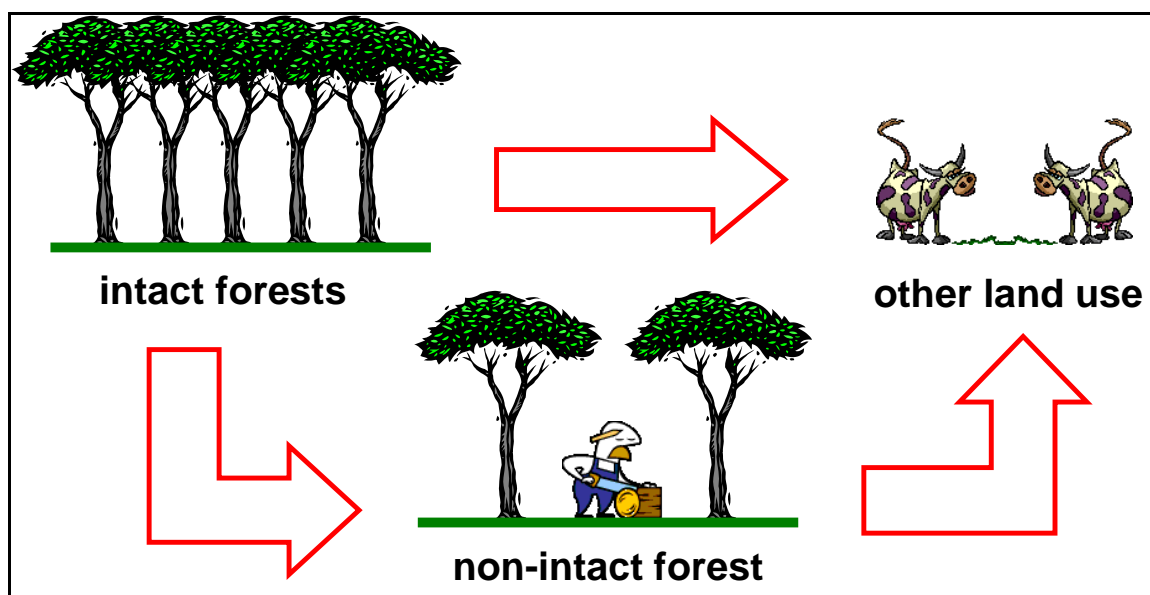
1319 1. Exclusion of areas around human settlements and infrastructure and residual
1320 fragments of landscape smaller than 5,000 ha, based on topographic maps, GIS
1321 database, thematic maps, etc. This first step could be done through a spatial
1322 analysis tool in a GIS software (this step could be fully automatic in case of good
1323 digital database on road networks). The result is a candidate set of landscape
1324 fragments with potential intact forest lands.

1325 2. Further exclusion of non-intact areas and delineation of intact forest lands is
1326 done by fine shaping of boundaries, based on visual interpretation methods of
1327 high-resolution satellite images (Landsat class data with 15-30 m pixel spatial
1328 resolution). Alternatively high-resolution satellite data could be used to develop a
1329 more detailed dataset on human infrastructures, that than could be used to
1330 delineate intact forest boundaries with a spatial analysis tool of a GIS software.

1331 The distinction between intact and non-intact allows us to account for carbon losses from
1332 forest degradation, reporting this as a conversion of intact to non-intact forest. The
1333 degradation process is thus accounted for as one of the three potential changes
1334 illustrated in Figure 2.1.4, i.e. from (i) intact forests to other land use, (ii) non-intact
1335 forests to other land use and (iii) intact forests to non-intact forests. In particular carbon
1336 emission from forest degradation for each forest type consists of two factors: the
1337 difference in carbon content between intact and non-intact forests and the area loss of
1338 intact forest area during the accounting period. This accounting strategy is fully
1339 compatible with the set of rules developed in the IPCC LULUCF Guidance and AFOLU
1340 Guidelines for the sections "Forest land remaining Forest land".

1341

1342 **Figure 2.1.4: Forest conversions types considered in the accounting system.**



1343

1344 The forest degradation is included in the conversion from intact to non-intact forest, and
1345 thus accounted as carbon stock change in that proportion of forest land remaining as
1346 forest land.

1347

1348 **Figure 2.1.5 Forest degradation**
1349 **assessment in Papua New Guinea**

1350 The Landsat satellite images (a) and
1351 (b) are representing the same
1352 portion of PNG territories in the Gulf
1353 Province and they have been
1354 acquired respectively in 26.12.1988
1355 and 07.10.2002. In this part of
1356 territory it is present only the
1357 lowland forest type.

1358 In the image (a) it is possible to
1359 recognize logging roads only on the
1360 east side of the river, while in the
1361 image (b) it is possible to recognize
1362 a very well developed logging road
1363 system also on the west side of the
1364 river. The forest canopy (brown-
1365 orange-red colours) does not seem
1366 to have evident changes in spectral
1367 properties (all these images are
1368 reflecting the same Landsat band
1369 combination 4,5,3).

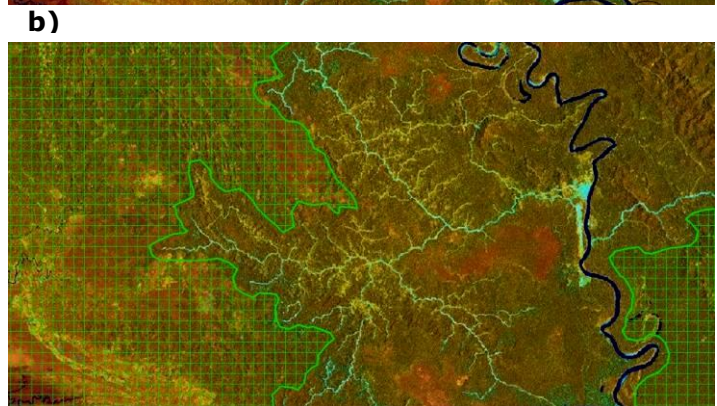
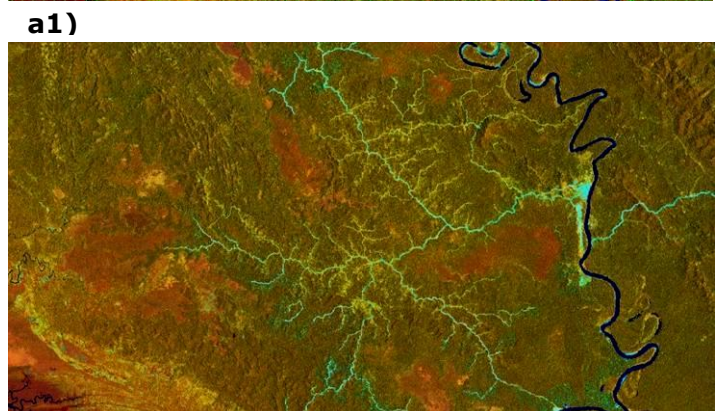
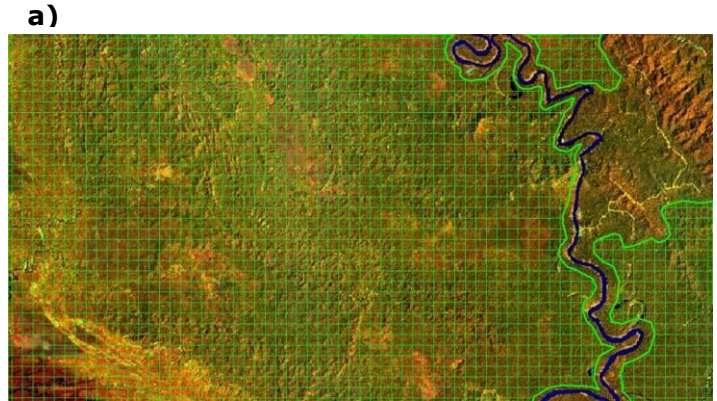
1370 The images (a1) and (b1) are
1371 respectively the same images (a)
1372 and (b) with some patterned
1373 polygons which are representing the
1374 extension of the intact forest in the
1375 respective dates. In this case an on-
1376 screen visual interpretation method
1377 have been used to delineate intact
1378 forest boundaries.

1379 In order to assess carbon emission
1380 from forest degradation for this part
1381 of its territory, PNG could report that
1382 in 14 years, 51% of the existing
1383 intact forest land has been converted
1384 to non-intact forest land. Thus the
1385 total carbon emission should be
1386 equivalent to the intact forest loss
1387 multiplied by the carbon content
1388 difference between intact and non-
1389 intact forest land.

1390 In this particular case, deforestation
1391 (road network) is accounting for less
1392 than 1%.

1393 Area size: ~ 20km x 10 km

1394



1395

1396 **2.1.4 Key references for Section 2.1**

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1439 **2.2 ESTIMATION OF ABOVE GROUND CARBON STOCKS**

1440 Tim Pearson, Winrock International, USA

1441 Nancy Harris, Winrock International, USA

1442 David Shoch, The Nature Conservancy, USA

1443 Sandra Brown, Winrock International, USA

1444

1445 **2.2.1 Scope of chapter**

1446 **Chapter 2.2 presents guidance on the estimation of the emission factors—the**
1447 **changes in above ground biomass carbon stocks of the forests being deforested**
1448 **and degraded. Guidance is provided on: (i) which of the three IPCC Tiers to be**
1449 **used, (ii) potential methods for the stratification by Carbon Stock of a country’s**
1450 **forests and (iii) actual Estimation of Carbon Stocks of Forests Undergoing**
1451 **Change.**

1452 Monitoring the location and areal extent of deforestation and degradation represents
1453 only one of two components involved in assessing emissions from deforestation and
1454 degradation. The other component is the emission factors—that is, the changes in
1455 carbon stocks of the forests being deforested and degraded that are combined with the
1456 activity data for deforestation and degradation for estimating the emissions.

1457

1458 In **Section 2.2.3** guidance is provided on: Which Tier Should be Used? The IPCC GL
1459 AFOLU allow for three Tiers with increasing complexity and costs of monitoring forest
1460 carbon stocks.

1461 In **Section 2.2.4** the focus is on: Stratification by Carbon Stock. As discussed in 2.2.1.1
1462 stratification is an essential step to allow an accurate, cost effective and creditable
1463 linkage between the remote sensing imagery estimates of areas deforested and
1464 estimates of carbon stocks and therefore emissions. In this section guidance is provided
1465 on potential methods for the stratification of a country’s forests.

1466 In **Section 2.2.5** guidance is given on the actual Estimation of above ground biomass
1467 Carbon Stocks of Forests Undergoing Change. Steps are given on how to devise and
1468 implement an inventory.

1469

1470 **2.2.2 Overview of carbon stocks, and issues related to C stocks**

1471

1472 **2.2.2.1 Issues related to carbon stocks**

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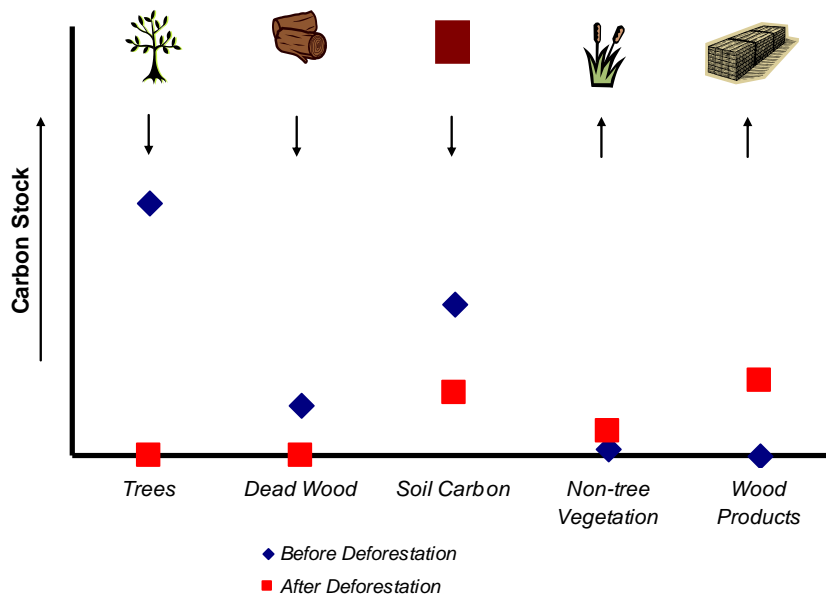
1474 **2.2.2.1.1 Fate of carbon pools as a result of deforestation and degradation**

1475 A forest is composed of pools of carbon stored in the living trees above and
1476 belowground, in dead matter including standing dead trees, down woody debris and

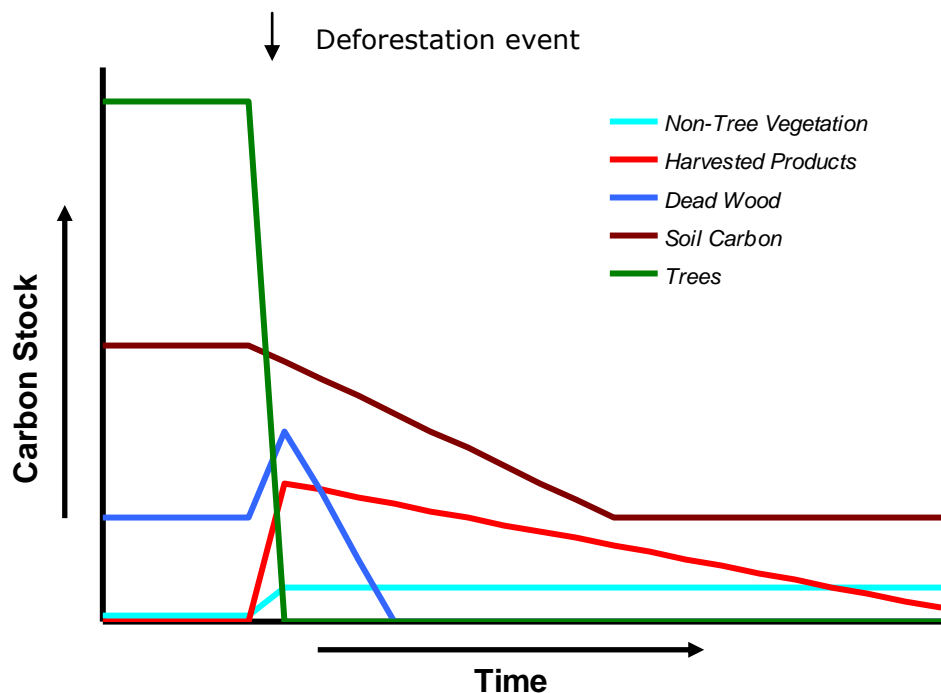
1477 litter, in non-tree understory vegetation and in the soil organic matter. When trees are
 1478 cut down there are three destinations for the stored carbon – dead wood, wood products
 1479 or the atmosphere.

- 1480 In all cases, following deforestation and degradation, the stock in living trees
 1481 decreases.
- 1482 Where degradation has occurred this is often followed by a recovery unless
 1483 continued anthropogenic pressure or altered ecologic conditions precludes tree
 1484 regrowth.
- 1485 The decreased tree carbon stock can either result in increased dead wood,
 1486 increased wood products or immediate emissions.
- 1487 Dead wood stocks may be allowed to decompose over time or may, after a given
 1488 period, be burned leading to further emissions.
- 1489 Wood products over time decompose, burned, or are retired to land fill.
- 1490 Where deforestation occurs, trees can be replaced by non-tree vegetation such as
 1491 grasses or crops. In this case, the new land-use has consistently lower plant
 1492 biomass and often lower soil carbon, particularly when converted to annual crops.
- 1493 Where a fallow cycle results, then periods of crops are interspersed with periods
 1494 of forest regrowth that may or may not reach the threshold for definition as
 1495 forest.

1496 Figure 2.2.1 below illustrates potential fates of existing forest carbon stocks after
 1497 deforestation.



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Figure 2.2.1: Fate of existing forest carbon stocks after deforestation.

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2.2.2.1.2 The need for stratification and how it relates to remote sensing data

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Carbon stocks vary by forest type, for example tropical pine forests will have a different stock than tropical broadleaf forests which will again have a different stock than a woodland or a mangrove forest. Even within broadleaf tropical forests, stocks will vary greatly with elevation, rainfall and soil type. Then even within a given forest type in a given location the degree of human disturbance will lead to further differences in stocks. The resolution of most readily and inexpensively available remote sensing imagery is not good enough to differentiate between different forest types or even between disturbed and undisturbed forest, and thus cannot differentiate different forest carbon stocks. Therefore stratifying forests can lead to more accurate and cost effective emission estimates associated with a given area of deforestation or degradation (see more on this topic below in section 2.2.4).

1513

2.2.3 Which Tier should be used?

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2.2.3.1 Explanation of IPCC Tiers

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The IPCC GPG and AFOLU Guidelines present three general approaches for estimating emissions/removals of greenhouse gases, known as "Tiers" ranging from 1 to 3 representing increasing levels of data requirements and analytical complexity. Despite differences in approach among the three tiers, all tiers have in common their adherence to IPCC good practice concepts of transparency, completeness, consistency, comparability, and accuracy.

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Tier 1 requires no new data collection to generate estimates of forest biomass. Default values for forest biomass and forest biomass mean annual increment (MAI) are obtained from the IPCC Emission Factor Data Base (EFDB), corresponding to broad continental forest types (e.g. African tropical rainforest). Tier 1 estimates thus provide limited resolution of how forest biomass varies sub-nationally and have a large error range (~ +/- 50% or more) for growing stock in developing countries (Box 2.2.1). The former is important because deforestation and degradation tend to be localized and hence may affect subsets of forest that differ consistently from a larger scale average (Figure 2.2.2). Tier 1 also uses simplified assumptions to calculate emissions. For deforestation, Tier 1 uses the simplified assumption of instantaneous emissions from woody vegetation,

1531 litter and dead wood. To estimate emissions from degradation (i.e. Forest remaining as
 1532 Forest), Tier 1 applies the gain-loss method (see Ch 5) using a default MAI combined
 1533 with losses reported from wood removals and disturbances, with transfers of biomass to
 1534 dead organic matter estimated using default equations.

Box 2.2.1. Error in Carbon Stocks from Tier 1 Reporting

To illustrate the error in applying Tier 1 carbon stocks for the carbon element of REDD reporting, a comparison is made here between the Tier 1 result and the carbon stock estimated from on-the-ground IPCC Good Practice-conforming plot measurements from six sites around the world. As can be seen in the table below, the IPCC Tier 1 predicted stocks range from 33 % higher to 44 % lower than a mean derived from plot measurements.

Location	IPCC Definition	Tier 1 Default (t C/ha)	Plot Measurements (t C/ha)	Tier 1 as % of Plot Measurements
Brazil	Tropical Rainforest, North and South America	150	218	-31
Mexico	Temperate Mountain Systems, North and South America	65	49	+33
Indonesia	Tropical Rainforest Asia Insular	175	212	-17
Republic of Congo	Tropical rainforest Africa	155	277	-44
Republic of Guinea	Tropical rainforest Africa	155	209	-26
Madagascar	Tropical rainforest Africa	155	148	+5

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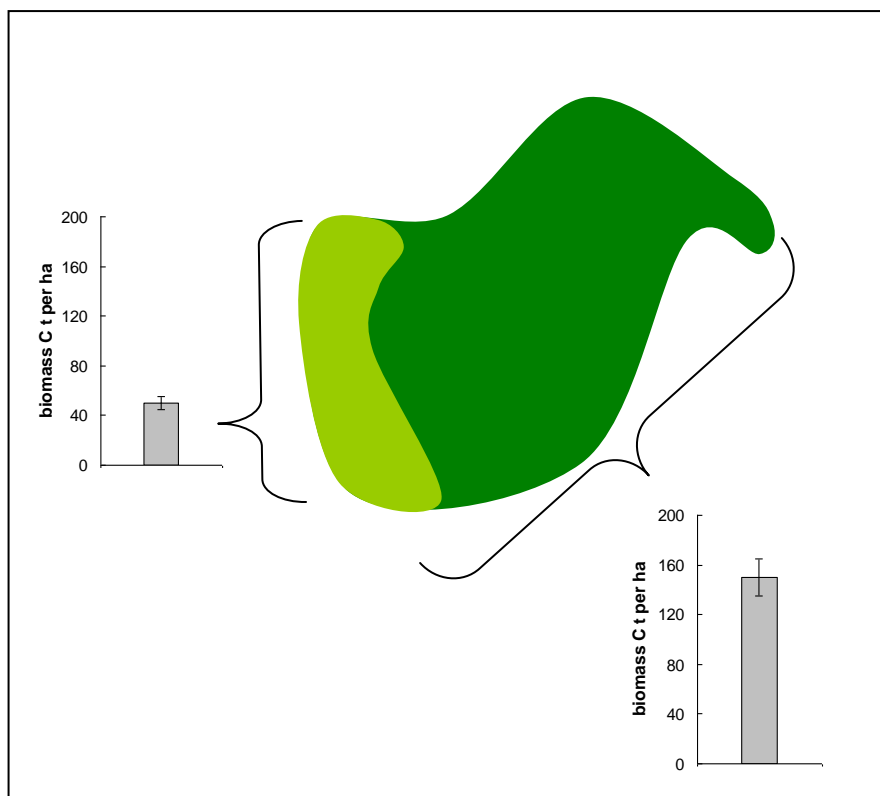
1544 Figure 2.2.2 below illustrates a hypothetical forest area, with a subset of the overall
 1545 forest, or strata, denoted in light green. Despite the fact that the forest overall (including
 1546 the light green strata) has an accurate and precise mean biomass stock of 150 t C/ha,
 1547 the light green strata alone has a significantly different mean biomass carbon stock (50 t
 1548 C/ha). Because deforestation often takes place along "fronts" (e.g. agricultural frontiers)
 1549 that may represent different subsets from a broad forest type (like the light green strata
 1550 at the periphery here) a spatial resolution of forest biomass carbon stocks is required to
 1551 accurately assign stocks to where loss of forest cover takes place. Assuming
 1552 deforestation was taking place in the light green area only and the analyst was not
 1553 aware of the different strata, applying the overall forest stock to the light green strata
 1554 alone would give inaccurate results, and that source of uncertainty could only be
 1555 discerned by subsequent ground-truthing.

1556 Figure 2.2.2 also demonstrates the inadequacies of extrapolating localized data across a
 1557 broad forest area, and hence the need to stratify forests according to expected carbon
 1558 stocks and to augment limited existing datasets (e.g. forest inventories and research
 1559 studies conducted locally) with supplemental data collection.

1560

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1562

Figure 2.2.2: A hypothetical forest area, with a subset of the overall forest, or strata, denoted in light green.



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1564 At the other extreme, Tier 3 is the most rigorous approach associated with the highest
1565 level of effort. Tier 3 uses actual inventories with repeated measures of permanent plots
1566 to directly measure changes in forest biomass and/or uses well parameterized models in
1567 combination with plot data. Tier 3 often focuses on measurements of trees only, and
1568 uses region/forest specific default data and modeling for the other pools. The Tier 3
1569 approach requires long-term commitments of resources and personnel, generally
1570 involving the establishment of a permanent organization to house the program (see
1571 section 3.2). The Tier 3 approach can thus be expensive in the developing country
1572 context, particularly where only a single objective (estimating emissions of greenhouse
1573 gases) supports the implementation costs. Unlike Tier 1, Tier 3 does not assume
1574 immediate emissions from deforestation, instead modeling transfers and releases among
1575 pools that more accurately reflect how emissions are realized over time. To estimate
1576 emissions from degradation, in contrast to Tier 1, Tier 3 uses the stock difference
1577 approach where change in forest biomass stocks is directly estimated from repeated
1578 measures or models.

1579 Tier 2 is akin to Tier 1 in that it employs static forest biomass information, but it also
1580 improves on that approach by using country-specific data (i.e. collected within the
1581 national boundary), and by resolving forest biomass at finer scales through the
1582 delineation of more detailed strata. Also, like Tier 3, Tier 2 can modify the Tier 1
1583 assumption that carbon stocks in woody vegetation, litter and deadwood are
1584 immediately emitted following deforestation (i.e. that stocks after conversion are zero),
1585 and instead develop disturbance matrices that model retention, transfers (e.g. from
1586 woody biomass to dead wood/litter) and releases (e.g. through decomposition and
1587 burning) among pools. For degradation, in the absence of repeated measures from a
1588 representative inventory, Tier 2 uses the gain-loss method using locally-derived data on
1589 mean annual increment. Done well, a Tier 2 approach can yield significant improvements
1590 over Tier 1 in reducing uncertainty, and though not as precise as repeated measures
1591 using permanent plots that can focus directly on stock change and increment, Tier 2
1592 does not require the sustained institutional backing.

1593 **2.2.3.2 Data needs for each Tier**

1594 The availability of data is another important consideration in the selection of an
 1595 appropriate Tier. Tier 1 has essentially no data collection needs beyond consulting the
 1596 IPCC tables and EFDB, while Tier 3 requires mobilization of resources where no national
 1597 forest inventory is in place (i.e. most developing countries). Data needs for each Tier are
 1598 summarized in Table 2.2.1.

1599 **Table 2.2.1: Data needs for meeting the requirements of the three IPCC Tiers**

Tier	Data needs/examples of appropriate biomass data
Tier 1 (basic)	Default MAI* (for degradation) and/or forest biomass stock (for deforestation) values for broad continental forest types—includes six classes for each continental area to encompass differences in elevation and general climatic zone; default values given for all vegetation-based pools
Tier 2 (intermediate)	MAI* and/or forest biomass values from existing forest inventories and/or ecological studies. Default values provided for all non-tree pools Newly-collected forest biomass data.
Tier 3 (most demanding)	Repeated measurements of trees from permanent plots and/or calibrated process models. Can use default data for other pools stratified by in-country regions and forest type, or estimates from process models.

1600 * MAI = Mean annual increment of tree growth

1601 **2.2.3.3 Selection of Tier**

1602 Tiers should be selected on the basis of goals (e.g. precise measure of emissions
 1603 reductions in the context of a performance-based incentives framework; conservative
 1604 estimate subject to deductions), the significance of the target source/sink, available
 1605 data, and analytical capability.

1606 **The IPCC recommends that it is good practice to use higher Tiers for the**
 1607 **measurement of significant sources/sinks.** To more clearly specify levels of data
 1608 collection and analytical rigor among sources of emissions/removals, the IPCC Guidelines
 1609 provide guidance on the identification of “Key Categories”. Key categories are sources of
 1610 emissions/removals that contribute substantially to the overall national inventory and/or
 1611 national inventory trends, and/or are key sources of uncertainty in quantifying overall
 1612 inventory amounts or trends. Key categories can be further broken down to identify
 1613 significant sub-categories or pools (e.g. above-ground biomass, below-ground biomass,
 1614 litter, and dead wood) that constitute > 25-30 % emissions/removals for the category.

1615 Due to the balance of costs and the requirement for accuracy/precision in the carbon
 1616 component of emission inventories, a Tier 2 methodology for carbon stock monitoring
 1617 will likely be the most widely used in both the reference period and for future monitoring
 1618 of emissions from deforestation and degradation. Although it is suggested that a Tier 3
 1619 methodology be the level to aim for key categories and pools, in practice Tier 3 may be
 1620 too costly to be widely used, at least in the near to mid term.

1621 On the other hand, Tier 1 will not deliver the accurate and precise measures needed for
 1622 key categories/pools by any mechanism in which economic incentives are foreseen.

1623 However, the principle of conservativeness will likely represent a fundamental parameter
1624 to evaluate REDD estimates. In that case, a tier lower than required could be used – or a
1625 carbon pool could be ignored - if it can be soundly demonstrated that the overall
1626 estimate of reduced emissions are underestimated (further explanation is given in
1627 section 4.4).

1628 Different tiers can be applied to different pools where they have a lower importance. For
1629 example, where preliminary observations demonstrate that emissions from the litter or
1630 dead wood or soil carbon pool constitute less than 25% of emissions from deforestation,
1631 the Tier 1 approach using default transfers and decomposition rates is justified for
1632 application to that pool.

1633 **2.2.4 Stratification by Carbon Stocks**

1634 Stratification refers to the division of any heterogeneous landscape into distinct sub-
1635 sections (or strata) based on some common grouping factor. In this case, the grouping
1636 factor is the stock of carbon in the vegetation. If multiple forest types are present across
1637 a country, stratification is the first step in a well-designed sampling scheme for
1638 estimating carbon emissions associated with deforestation and degradation over both
1639 large and small areas. Stratification is the critical step that will allow the association of a
1640 given area of deforestation and degradation with an appropriate vegetation carbon stock
1641 for the calculation of emissions.

1642 **2.2.4.1 Why stratify?**

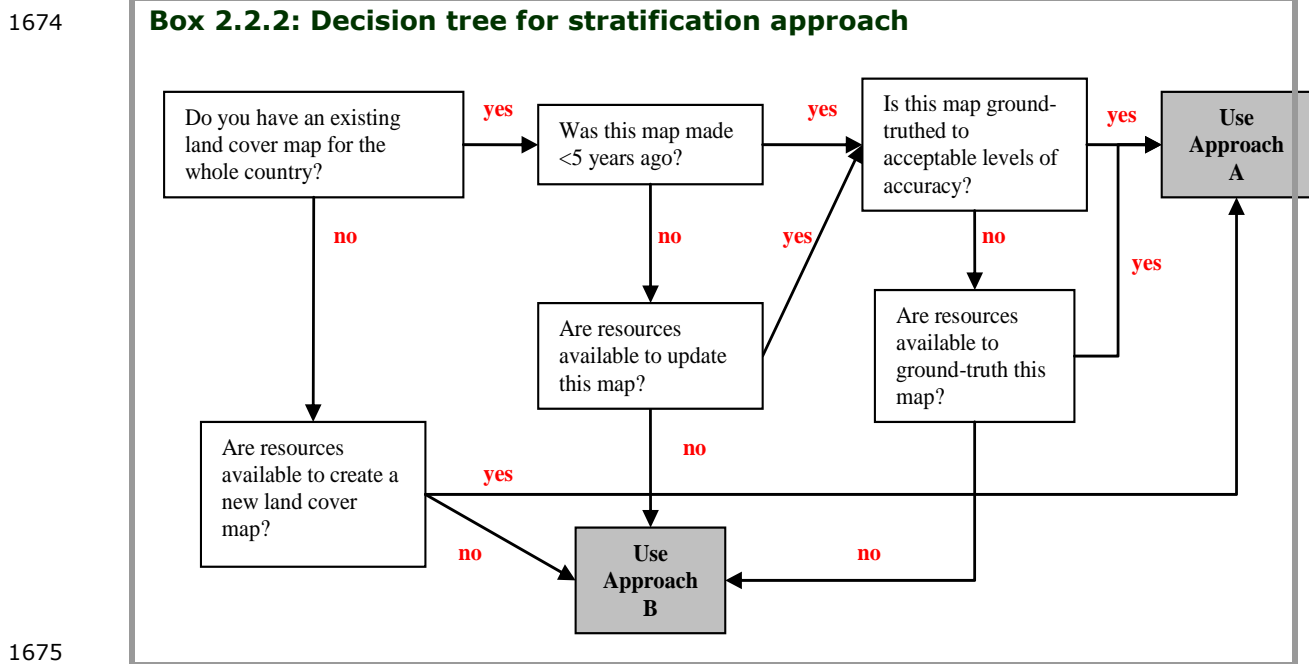
1643 Different carbon stocks exist in different forest types and ecoregions depending on
1644 physical factors (e.g., precipitation regime, temperature, soil type, topography),
1645 biological factors (tree species composition, stand age, stand density) and anthropogenic
1646 factors (disturbance history, logging intensity). For example, secondary forests have
1647 lower carbon stocks than mature forests and logged forests have lower carbon stocks
1648 than unlogged forests. Associating a given area of deforestation with a specific carbon
1649 stock that is relevant to the location that is deforested or degraded will result in more
1650 accurate and precise estimates of carbon emissions. This is the case for all levels of
1651 deforestation assessment from a very coarse Tier 1 assessment to a highly detailed Tier
1652 3 assessment.

1653 Because ground sampling is usually required to determine appropriate carbon estimates
1654 for the specific areas that were deforested or degraded, stratifying an area by its carbon
1655 stocks can **increase accuracy and precision and reduce costs**. National carbon
1656 accounting needs to emphasize a system in which stratification and refinement are based
1657 on carbon content (or expected reductions in carbon content) of specific forest types, not
1658 necessarily of forest vegetation. For example, the carbon stocks of a “tropical rain forest”
1659 (one vegetation class) may be vastly different with respect to carbon stocks depending
1660 on its geographic location and degree of disturbance.

1661 **2.2.4.2 Approaches to stratification**

1662 There are two different approaches for stratifying forests for national carbon accounting,
1663 both of which require some spatial information on forest cover within a country. In
1664 Approach A, all of a country’s forests are stratified ‘up-front’ and carbon estimates are
1665 made to produce a country-wide map of forest carbon stocks. At future monitoring
1666 events, only the activity data need to be monitored and combined with the pre-
1667 estimated carbon stock values. In Approach B, a full land cover map of the whole
1668 country does not need to be created. Rather, carbon estimates are made at each
1669 monitoring event only in those areas that have undergone change. Which approach to
1670 use depends on a country’s access to relevant and up-to-date data as well as its financial
1671 and technological resources. See Box 2.2.2 that provides a decision tree that can be

1672 used to select which stratification approach to use. Details of each approach are outlined
1673 below.



1675

1676

1677 **Approach A: 'Up-front' stratification using existing or updated land cover maps**

1678 The first step in stratifying by carbon stocks is to determine whether a national land
1679 cover or land use map already exists. This can be done by consulting with government
1680 agencies, forestry experts, universities, the FAO, internet, and the like who may have
1681 created these maps for other purposes.

1682 Before using the existing land cover or land use map for stratification, its quality and
1683 relevance should be assessed. For example:

1684 When was the map created? Land cover change is often rapid and therefore a
1685 land cover map that was created more than five years ago is most likely out-of-
1686 date and no longer relevant. If this is the case, a new land cover map should be
1687 created. To participate in REDD activities it is likely a country will need to have at
1688 least a land cover map for a relatively recent time (benchmark map—see section
1689 2.1).

1690 Is the existing map at an appropriate resolution for your country's size and land
1691 cover distribution? Land cover maps derived from coarse-resolution satellite
1692 imagery may not be detailed enough for very small countries and/or for countries
1693 with a highly patchy distribution of forest area. For most countries, land cover
1694 maps derived from medium-resolution imagery (e.g., 30-m resolution Landsat
1695 imagery) are adequate (cf. section 2.1).

1696 Is the map ground validated for accuracy? An accuracy assessment should be
1697 carried out before using any land cover map in additional analyses. Guidance on
1698 assessing the accuracy of remote sensing data is given in section 2.6.

1699 Land cover and land use maps are sometimes produced for different purposes and
1700 therefore the classification may not be fully useable in their current form. For example, a
1701 land use map may classify all forest types as one broad 'forest' category, which would
1702 not be valuable for stratification unless more detailed information was available to
1703 supplement this map. Indicator maps are valuable for adding detail to broadly defined
1704 forest categories (see Box 2.2.3 for examples), but should be used judiciously to avoid

1705 overcomplicating the issue. In most cases, overlaying one or two indicator maps
 1706 (elevation and distance to transportation networks, for example) with a forest/non-forest
 1707 land cover map should be adequate for delineating forest strata by carbon stocks.

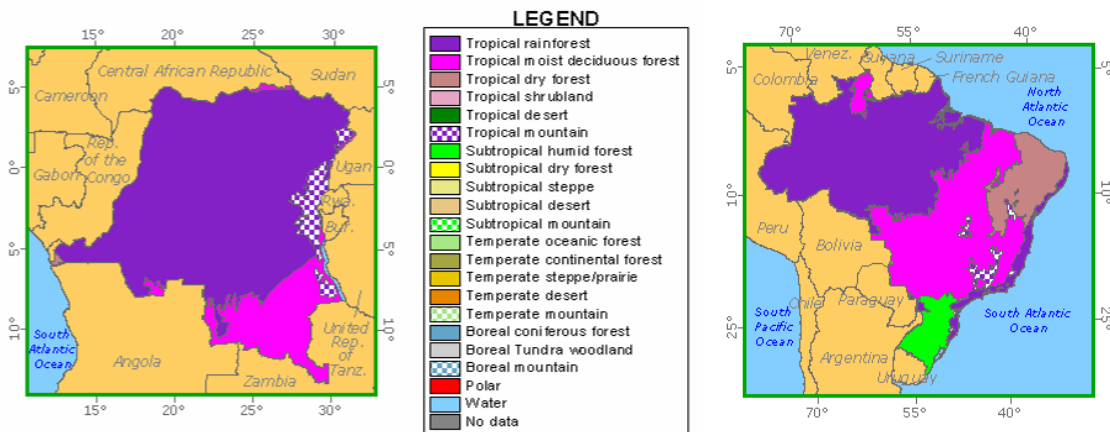
1708 Once strata are delineated on a ground-validated land cover map and forest types have
 1709 been identified, carbon stocks are estimated for each stratum using appropriate
 1710 measuring and monitoring methods. A national map of carbon stocks can then be
 1711 created (cf Section 2.2.4).

Box 2.2.3: Examples of maps on which a land use stratification can be built

Ecological zone maps

One option for countries with virtually no data on carbon stocks is to stratify the country initially by ecological zone or ecoregion using global datasets. Examples of these maps include:

1. Holdridge life zones (<http://geodata.grid.unep.ch/>)
2. WWF ecoregions (<http://www.worldwildlife.org/science/data/terreco.cfm>)
3. FAO ecological zones (<http://www.fao.org/geonetwork/srv/en/main.home>, type 'ecological zones' in search box)



Indicator maps

After ecological zone maps are overlain with maps of forest cover to delineate where forests within different ecological zones are located, there are several indicators that could be used for further stratification. These indicators can be either biophysically- or anthropogenically-based:

Biophysical indicator maps

- Elevation
- Topography (slope and aspect)
- Soils
- Forest Age (if known)
- Areas of protected forest

Anthropogenic indicator maps:

- Distance to deforested land or forest edge
- Distance to towns and villages
- Proximity to transportation networks (roads, rivers)
- Rural population density

In Approach A, all of the carbon estimates would be made once, up-front, i.e., at the beginning of monitoring program, and no additional carbon estimates would be necessary for the remainder of the monitoring period - only the activity data would need to be monitored. This does assume that the carbon stocks in the original forests being monitored would not change much over about 10-20 years—such a situation is likely to

1740 exist where most of the forests are relatively intact, have been subject to low intensity
1741 selective logging in the past, no major infrastructure exists in the areas, and/or are at a
1742 late secondary stage (> 40-50 years). When the forests in question do not meet the
1743 aforementioned criteria, then new estimates of the carbon stocks could be made based
1744 on measurements taken more frequently—up to less than 10 years.

1745 As ecological zone maps are a global product, they tend to be very broad and hence
1746 certain features of the landscape that affect carbon stocks within a country are not
1747 accounted for. For example, a country with mountainous terrain would benefit from
1748 using elevation data (such as a digital elevation model) to stratify ecological zones into
1749 different elevational sub-strata because forest biomass is known to decrease with
1750 elevation. Another example would be to stratify the ecological zone map by soil type as
1751 forests on loamy soils tend to have higher growth potential than those on very sandy or
1752 very clayey soils. If forest degradation is common in your country, stratifying ecological
1753 zones by distance to towns and villages or to transportation networks may be useful. An
1754 example of how to stratify a country with limited data is shown in Box 2.2.4.

1755

1756

1757

Box 2.2.4: Forest stratification in countries with limited data availability

1758

An example stratification scheme is shown here for the Democratic Republic of Congo.

1759

1760

Step 1. Overlay a map of forest cover with an ecological zone map (A).

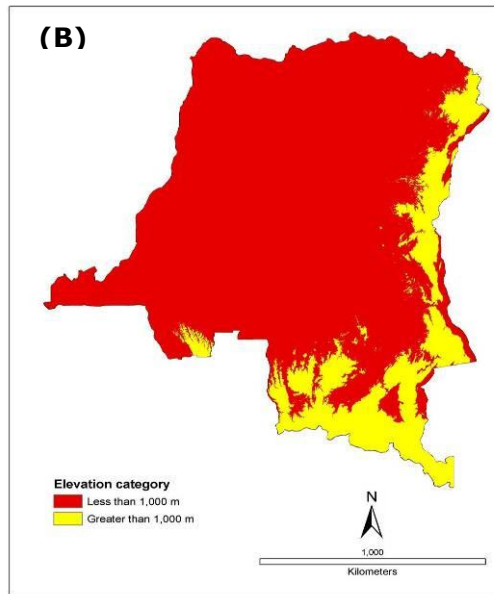
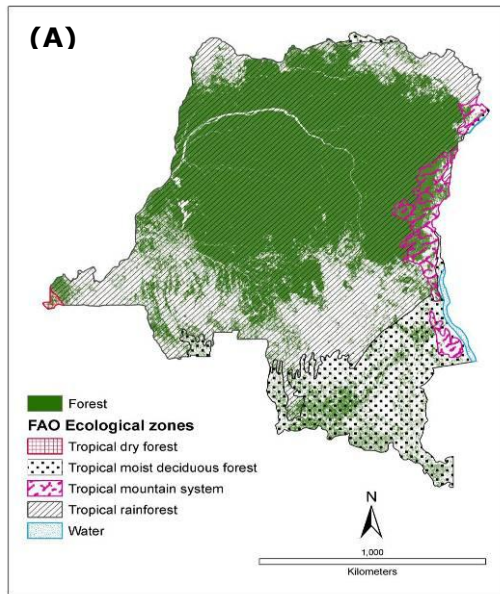
1761

Step 2. Select indicator maps. For this example, elevation (B) and distance to roads (C) were chosen as indicators.

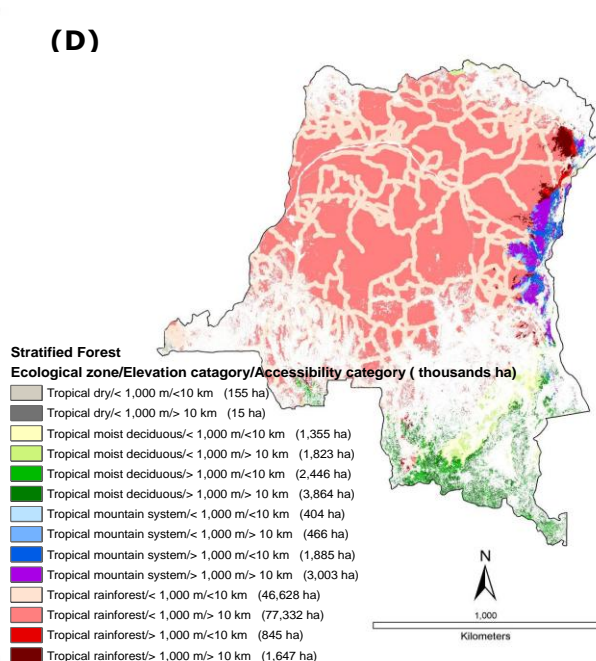
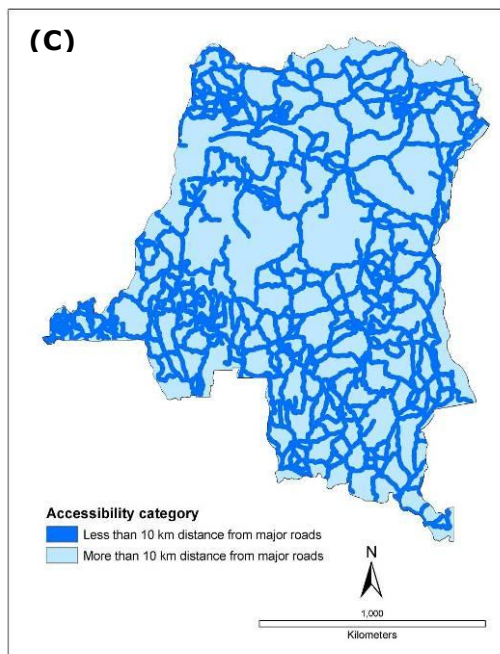
1762

1763

Step 3. Combine all factors to create a map of forest strata (D).



1764



1765

1766

1767

1768

1769 **Approach B: Continuous stratification based on a continuous carbon inventory**

1770 Where wall-to-wall land cover mapping is not possible for stratifying forest area within a
1771 country by carbon stocks, regularly-timed "inventories" can be made by sampling only
1772 the areas subject to deforestation and degradation. Using this approach, a full land cover
1773 map for the whole country is not necessary because carbon assessment occurs only
1774 where land cover change occurred (forest to non-forest, or intact to degraded forest in
1775 some cases). Carbon measurements can then be made in neighboring pixels that have
1776 the same reflectance/textural characteristics as the pixels that had undergone change in
1777 the previous interval, serving as proxies for the sites deforested or degraded, and carbon
1778 emissions can be calculated.

1779 This approach is likely the least expensive option as long as neighboring pixels to be
1780 measured are relatively easy to access by field teams. However, this approach is not
1781 recommended when vast areas of contiguous forest are converted to non-forest,
1782 because the forest stocks may have been too spatially variable to estimate a single
1783 proxy carbon value for the entire forest area that was converted. If this is the case, a
1784 conservative approach would be to use the lowest carbon stock estimate for the forest
1785 area that was converted to calculate emissions in the reference case and the highest
1786 carbon stock estimate in the monitoring phase.

1787 **2.2.5 Estimation of Carbon Stocks of Forests Undergoing Change**

1788 **2.2.5.1 Decisions on which carbon pools to include**

1789 The decision on which carbon pools to monitor as part of a REDD accounting scheme will
1790 likely be governed by the following factors:

- 1791 Available financial resources
- 1792 Availability of existing data
- 1793 Ease and cost of measurement
- 1794 The magnitude of potential change in the pool
- 1795 The principle of conservativeness

1796 Above all is the principle of conservativeness. This principle ensures that reports of
1797 decreases in emissions are not overstated. **Clearly for this purpose both time-zero
1798 and subsequent estimations must include exactly the same pools.**
1799 Conservativeness also allows for pools to be omitted except for the dominant tree carbon
1800 pool and a precedent exists for Parties to select which pools to monitor within the Kyoto
1801 Protocol and Marrakesh Accords (see section 4.4 for further discussion on
1802 conservativeness). For example, if dead wood or wood products are omitted then the
1803 assumption must be that all the carbon sequestered in the tree is immediately emitted
1804 and thus deforestation or degradation estimates are under-estimated. Likewise if CO₂
1805 emitted from the soil is excluded as a source of emissions; and as long as this exclusion
1806 is constant between the reference case and later estimations, then no exaggeration of
1807 emissions reductions occurs.

1808 **2.2.5.1.1 Key categories**

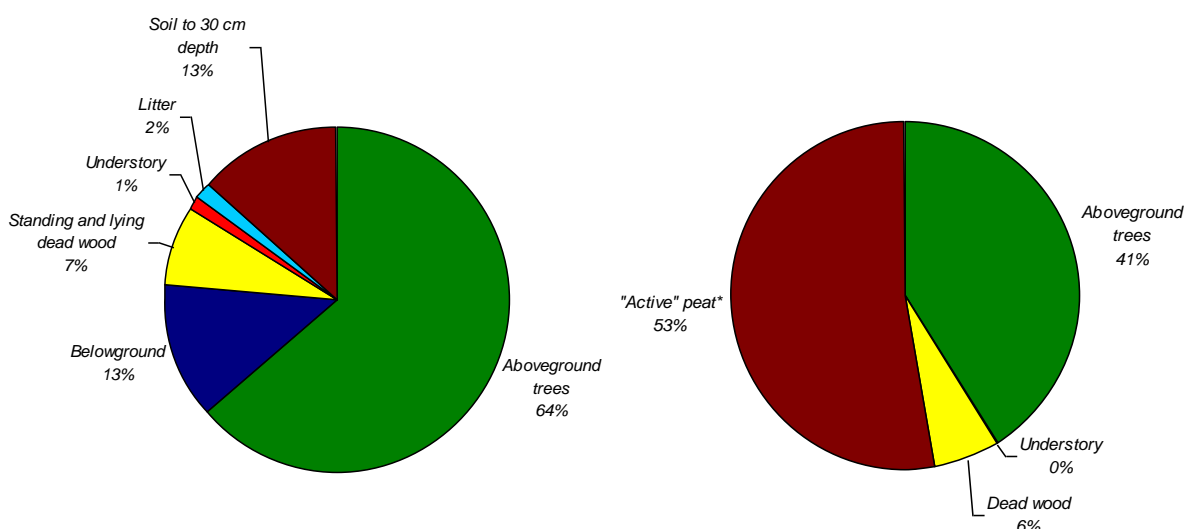
1809 The second deciding factor on which carbon pools to include should be the relative
1810 importance of the expected change in each of the carbon pools caused by deforestation
1811 and degradation. The magnitude of the carbon pool basically represents the magnitude
1812 of the emissions for deforestation as it is typically assumed that most of the pool is
1813 oxidized, either on or off site. For degradation the relationship is not as clear as usually
1814 only the trees are affected for most causes of degradation (cf. Ch. 3.3).

1815 In all cases it will make sense to include trees, as trees are relatively easy to measure
1816 and will always represent a significant proportion of the total carbon stock. The

1817 remaining pools will represent varying proportions of total carbon depending on local
 1818 conditions. For example, belowground biomass carbon (roots) and soil carbon to 30 cm
 1819 depth represents 26% of total carbon stock in estimates in tropical lowland forests of
 1820 Bolivia but more than 50 % in the peat forests of Indonesia (Figure 2.2.3 a & b²¹). It is
 1821 also possible that which pools are included or not varies by forest type/strata within a
 1822 country. It is possible that say forest type A in a given country could have relatively high
 1823 carbon stocks in the dead wood and litter pools, whereas forest type B in the country
 1824 could have low quantities in these pools—in this case it might make sense to measure
 1825 these pools in the forest A but not B as the emissions from deforestation would be higher
 1826 in A than in B.

1827 **Figure 2.2.3:** LEFT- Proportion of total stock (202 t C/ha) in each carbon pool in Noel
 1828 Kempff Climate Action project (a pilot carbon project), Bolivia, and RIGHT- Proportion of
 1829 total stock (236 t C/ha) in each carbon pool in peat forest in Central Kalimantan,
 1830 Indonesia (active peat includes soil organic carbon, live and dead roots, and
 1831 decomposing materials).

1832



1833

1834 Pools can be divided by ecosystem and land use change type into key categories or
 1835 minor categories. Key categories represent pools that could account for more than 25%
 1836 of the total emissions resulting from the deforestation or degradation (Table 2.2.2).

1837

1838 **Table 2.2.2: Broad guidance on key categories of carbon pools for determining**
 1839 **assessment emphasis.** Key category defined as pools potentially responsible for more
 1840 than 25% of total emission resulting from the deforestation or degradation.

	Biomass		Dead organic matter		Soils
	Aboveground	Below-ground	Dead wood	Litter	Soil organic matter
	Deforestation				
To cropland	KEY	KEY	(KEY)		KEY
To pasture	KEY	KEY	(KEY)		

²¹Brown, S. 2002, Measuring, monitoring, and verification of carbon benefits fro forest-based projects. Phil. Trans. R. Soc. Lond. A. 360: 1669-1683, and unpublished data from measurements by Winrock

To shifting cultivation	KEY	KEY	(KEY)
Degradation			
Degradation	KEY	KEY	(KEY)

1841

1842 Certain pools such as soil carbon or even down dead material tend to be quite variable
 1843 and can be relatively time consuming and costly to measure. The decision to include
 1844 these pools would therefore be made based on whether they represent a key category
 1845 and available financial resources.

1846 Soils will represent a key category in peat swamp forests and mangrove forests and
 1847 carbon emissions are high when deforested (cf section 2.3). For forests on mineral soils
 1848 with high organic carbon content and deforestation is to cropland, as much as 30-40% of
 1849 the total soil organic matter stock can be lost in the top 30 cm or so during the first 5
 1850 years. Where deforestation is to pasture or shifting cultivation, the science does not
 1851 support a large drop in soil carbon stocks.

1852 Dead wood is a key category in old growth forest where it can represent more than 10%
 1853 of total biomass, in young successional forests, for example, it will not be a key
 1854 category.

1855 For carbon pools representing a fraction of the total (<25 %) it may be possible to
 1856 include them at low cost if good default data are available.

1857 Box 2.2.5 provides examples that illustrate the scale of potential emissions from just the
 1858 aboveground biomass pool following deforestation and degradation in Bolivia, the
 1859 Republic of Congo and Indonesia.

1860

1861

Box 2.2.5: Potential emissions from deforestation and degradation in three example countries

1862

1863

1864

1865

1866

The following table shows the decreases in the carbon stock of living trees estimated for both deforestation, and degradation through legal selective logging for three countries: Republic of Congo, Indonesia, and Bolivia. The large differences among the countries for degradation reflects the differences in intensity of timber extraction (about 3 to 22 m³/ha).

	Republic of Congo	Indonesia	Bolivia
	<i>t CO₂/ha</i>		
Degradation	26	88	17
Deforestation	1,015	777	473

1867

1868

2.2.5.1.2 Defining carbon measurement pools:

1869

STEP 1: INCLUDE ABOVEGROUND TREE BIOMASS

1870

1871

1872

All assessments should include aboveground tree biomass as the carbon stock in this pool is simple to measure and estimate and will almost always dominate carbon stock changes

1873

STEP 2: INCLUDE BELOWGROUND TREE BIOMASS

1874

1875

1876

Belowground tree biomass (roots) is almost never measured, but instead is included through a relationship to aboveground biomass (usually a root-to-shoot ratio). If the vegetation strata correspond with tropical or subtropical types listed in [Table 2.2.3](#)

1877 (modified from Table 2.2.4 in IPCC GL AFOLU to exclude non-forest or non-tropical
 1878 values and to account for incorrect values) then it makes sense to include roots.

1879

1880 **Table 2.2.3: Root to shoot ratios modified* from Table 4.4. in IPCC GL AFOLU**

Domain	Ecological Zone	Above-ground biomass	Root-to-shoot ratio	Range
Tropical	Tropical rainforest	<125 t.ha-1	0.20	0.09-0.25
		>125 t.ha-1	0.24	0.22-0.33
	Tropical dry forest	<20 t.ha-1	0.56	0.28-0.68
		>20 t.ha-1	0.28	0.27-0.28
Subtropical	Subtropical humid forest	<125 t.ha-1	0.20	0.09-0.25
		>125 t.ha-1	0.24	0.22-0.33
	Subtropical dry forest	<20 t.ha-1	0.56	0.28-0.68
		>20 t.ha-1	0.28	0.27-0.28

1881 *the modification corrects an error in the table based on communications with Karel
 1882 Mulrone, the lead author of the peer reviewed paper from which the data were
 1883 extracted.

1884 **STEP 3: ASSESS THE RELATIVE IMPORTANCE OF ADDITIONAL CARBON POOLS**

1885 Assessment of whether other carbon pools represent key categories can be conducted
 1886 via a literature review, discussions with universities or even field measurements from a
 1887 few pilot plots following methodological guidance already provided in many of the
 1888 sources given in this section.

1889 **STEP 4: DETERMINE IF RESOURCES ARE AVAILABLE TO INCLUDE ADDITIONAL
 1890 POOLS**

1891 When deciding if additional pools should be included or not, it is important to remember
 1892 that whichever pools are decided on initially the same pools must be included in all
 1893 future monitoring events. Although national or global default values can be used, if they
 1894 are a key category they will make the overall emissions estimates more uncertain.
 1895 However, it is possible that once a pool is selected for monitoring, default values could
 1896 be used initially with the idea of improving these values through time, but even if just a
 1897 one time measurement will be the basis of the monitoring scheme, there are costs
 1898 associated with including additional pools. For example:

- 1899 for soil carbon—soil is collected and then must be analyzed in a laboratory for
 1900 bulk density and percent soil carbon
- 1901 for non-tree vegetation—destructive sampling is usually employed with samples
 1902 collected and dried to determine biomass and carbon stock
- 1903 for down dead wood—stocks are usually assessed along a transect with the
 1904 simultaneous collection and subsequent drying of samples for density

1905 If the pool is a significant source of emissions as a result of deforestation or degradation
 1906 it will be worth including it in the assessment if it is possible. An alternative to
 1907 measurement for minor carbon pools (<25% of the total potential emission) is to include
 1908 estimates from tables of default data with high integrity (peer-reviewed).

1909 **2.2.5.2 General approaches to estimation of carbon stocks**

1910 **2.2.5.2.1 Step 1: Identify strata where assessment of carbon stocks is**
1911 **necessary**

1912 Not all forest strata are likely to undergo deforestation or degradation. For example,
1913 strata that are currently distant from existing deforested areas and/or inaccessible from
1914 roads or rivers are unlikely to be under immediate threat. Therefore, a carbon
1915 assessment of every forest stratum within a country would not be cost-effective because
1916 not all forests will undergo change.

1917 For stratification approach B (described above), where and when to conduct a carbon
1918 assessment over each monitoring period is defined by the activity data, with
1919 measurements taking place in nearby areas that currently have the same reflectance as
1920 the changed pixels had prior to deforestation or degradation. For stratification approach
1921 A, the best strategy would be to invest in carbon stock assessments for strata where
1922 there is a history or future likelihood of degradation or deforestation, not for strata
1923 where there is little deforestation pressure.

1924 SubStep 1 – For reference emission case (and future monitoring for approach B):
1925 establish sampling plans in areas representative of the areas with recorded deforestation
1926 and/or degradation.

1927 SubStep 2 – For future monitoring: identify strata where deforestation and/or
1928 degradation are likely to occur. These will be strata adjoining existing deforested areas
1929 or degraded forest, and/or strata with human access via roads or easily navigable
1930 waterways. Establish sampling plans for these strata but, for the current period, do not
1931 invest in measuring forests that are hard to access such as areas that are distant to
1932 transportation routes, towns, villages and existing farmland, and/or areas at high
1933 elevations or that experience very heavy rainfall.

1934 **2.2.5.2.2 Step 2: Assess existing data**

1935 It is likely that within most countries there will be some data already collected that could
1936 be used to define the carbon stocks of one or more strata. These data could be derived
1937 from a forest inventory or perhaps from past scientific studies. Proceed with
1938 incorporating these data if the following criteria are fulfilled:

- 1939 The data are less than 10 years old
- 1940 The data are derived from multiple measurement plots
- 1941 All species must be included in the inventories
- 1942 The minimum diameter for trees included is 30cm or less at breast height
- 1943 Data are sampled from good coverage of the strata over which they will be
1944 extrapolated

1945 Existing data that meet the above criteria should be applied across the strata from which
1946 they were representatively sampled and not beyond that. The existing data will likely be
1947 in one of two forms:

- 1948 Forest inventory data
- 1949 Data from scientific studies

1950 **Forest inventory data**

1951 Typically forest inventories have an economic motivation. As a consequence, forest
1952 inventories worldwide are derived from good sampling design. If the inventory can be
1953 applied to a stratum, all species are included and the minimum diameter is 30 cm or less
1954 then the data will be a high enough quality with sufficiently low uncertainty for inclusion.
1955 Inventory data typically comes in two different forms:

1956 **Stand tables**—these data from an inventory are potentially the most useful from which
 1957 estimates of the carbon stock of trees can be calculated. Stand tables generally include a
 1958 tally of all trees in a series of diameter classes. The method basically involves estimating
 1959 the biomass per average tree of each diameter (diameter at breast height, dbh) class of
 1960 the stand table, multiplying by the number of trees in the class, and summing across all
 1961 classes. The mid-point diameter of the class can be used²² in combination with an
 1962 allometric biomass regression equation. Guidance on choice of equation and application
 1963 of equations is widely available (for example see sources in Box 4-9). For the open-
 1964 ended largest diameter classes it is not obvious what diameter to assign to that class.
 1965 Sometimes additional information is included that allows educated estimates to be made,
 1966 but this is often not the case. The default assumption should be to assume the same
 1967 width of the diameter class and take the midpoint, for example if the highest class is
 1968 >110 cm and the other class are in 10 cm bands, then the midpoint to apply to the
 1969 highest class should be 115 cm.

1970 It is important that the diameter classes are not overly large so as to decrease how
 1971 representative the average tree biomass is for that class. Generally the rule should be
 1972 that the width of diameter classes should not exceed 15 cm.

1973 Sometimes, the stand tables only include trees with a minimum diameter of 30 cm or
 1974 more, which essentially ignores a significant amount of carbon particularly for younger
 1975 forests or heavily logged. To overcome the problem of such incomplete stand tables, an
 1976 approach has been developed for estimating the number of trees in smaller diameter
 1977 classes based on number of trees in larger classes²³. It is recommended that the method
 1978 described here (Box 2.2.6) be used for estimating the number of trees in one to two
 1979 small classes only to complete a stand table to a minimum diameter of 10 cm.

1980

Box 2.2.6: Adding diameter classes to truncated stand tables

DBH Class (cm)	Midpoint Diameter (cm)	Number of Stems per ha
10-19	15	-
20-29	25	-
30-39	35	35.1
40-49	45	11.8
50-59	55	4.7
...

1981

1982 dbh class 1= 30-39 cm, and dbh class 2= 40-49 cm

1983 Ratio = $35.1/11.8 = 2.97$

1984 Therefore, the number of trees in the 20-29 cm class is: $2.97 \times 35.1 = 104.4$

1985 To calculate the 10-19 cm class: $104.4/35.1 = 2.97,$

1986 $2.97 \times 104.4 = 310.6$

²² If information on the basal area of all the trees in each diameter class is provided, instead of using the mid point of the diameter class the quadratic mean diameter (QMD) can be used instead—this is the diameter of the tree with the average basal area (=basal area of trees in class/#trees).

²³ Gillespie, A. J. R, S. Brown, and A. E. Lugo. 1992. Tropical forest biomass estimation from truncated stand tables. *Forest Ecology and Management* 48:69-88.

1987 The method is based on the concept that uneven-aged forest stands have a
 1988 characteristic "inverse J-shaped" diameter distribution. These distributions have a large
 1989 number of trees in the small classes and gradually decreasing numbers in medium to
 1990 large classes. The best method is the one that estimated the number of trees in the
 1991 missing smallest class as the ratio of the number of trees in dbh class 1 (the smallest
 1992 reported class) to the number in dbh class 2 (the next smallest class) times the number
 1993 in dbh class 1 (demonstrated in Box 2.2.3 to 2.2.6).

1994 **Stock tables**—a table of the merchantable volume is sometimes available, often by
 1995 diameter class or total per hectare. If stand tables are not available, it is likely that
 1996 volume data are available if a forestry inventory has been conducted somewhere in the
 1997 country. In many cases volumes given will be of just commercial species. If this is the
 1998 case then these data can not be used for estimating carbon stocks, as a large and
 1999 unknown proportion of total volume and therefore total biomass is excluded.

2000 Biomass density can be calculated from volume over bark of merchantable growing stock
 2001 wood (VOB) by "expanding" this value to take into account the biomass of the other
 2002 aboveground components—this is referred to as the biomass conversion and expansion
 2003 factor (BCEF). When using this approach and default values of the BCEF provided in the
 2004 IPCC AFOLU, it is important that the definitions of VOB match. The values of BCEF for
 2005 tropical forests in the AFOLU report are based on a definition of VOB as follows:

2006 Inventoried volume over bark of free bole, i.e. from stump or buttress to crown point or
 2007 first main branch. Inventoried volume must include all trees, whether presently
 2008 commercial or not, with a minimum diameter of 10 cm at breast height or above
 2009 buttress if this is higher.

2010 Aboveground biomass (t/ha) is then estimated as follows: = VOB * BCEF²⁴

2011 where:

2012 BCEF t/m³ = biomass conversion and expansion factor (ratio of aboveground oven-dry
 2013 biomass of trees [t/ha] to merchantable growing stock volume over bark [m³/ha]).

2014 Values of the BCEF are given in Table 4.5 of the IPCC AFOLU, and those relevant to
 2015 tropical humid broadleaf and pine forests are shown in the Table 2.2.4.

2016 **Table 2.2.4: Values of BCEF (average and range) for application to volume data.**
 2017 (Modified from Table 4.5 in IPCC AFOLU)

Forest type	Growing stock volume –range (VOB, m ³ /ha)						
	<20	21-40	41-60	61-80	80-120	120-200	>200
Natural broadleaf	4.0	2.8	2.1	1.7	1.5	1.3	1.0
	2.5-12.0	1.8-304	1.2-2.5	1.2-2.2	1.0-1.8	0.9-1.6	0.7-1.1
Conifer	1.8	1.3	1.0	0.8	0.8	0.7	0.7
	1.4-2.4	1.0-1.5	0.8-1.2	0.7-1.2	0.6-1.0	1.6-0.9	0.6-0.9

2018

2019 In cases where the definition of VOB does not match exactly the definition given above,
 2020 a range of BCEF values are given:

- 2021 If the definition of VOB also includes stem tops and large branches then the lower
 2022 bound of the range for a given growing stock should be used

²⁴ This method from the IPCC AFOLU replaces the one reported in the IPCC GPG. The GPG method uses a slightly different equation :AGB = VOB*wood density*BEF; where BEF, the biomass expansion factor, is the ratio of aboveground biomass to biomass of the merchantable volume in this case.

2023 If the definition of VOB has a large minimum top diameter or the VOB is
2024 comprised of trees with particularly high basic wood density then the upper bound
2025 of the range should be used

2026 Forest inventories often report volumes to a minimum diameter greater than 10 cm.
2027 These inventories may be the only ones available. To allow the inclusion of these
2028 inventories, volume expansion factors (VEF) were developed. After 10 cm, common
2029 minimum diameters for inventoried volumes range between 25 and 30 cm. Due to high
2030 uncertainty in extrapolating inventoried volume based on a minimum diameter of larger
2031 than 30 cm, inventories with a minimum diameter that is higher than 30 cm should not
2032 be used. Volume expansion factors range from about 1.1 to 2.5, and are related to the
2033 VOB30 as follows to allow conversion of VOB30 to a VOB10 equivalent:

$$\begin{aligned} \text{2034 VEF} &= \text{Exp}\{1.300 - 0.209 \cdot \text{Ln}(\text{VOB30})\} \text{ for VOB30} < 250 \text{ m}^3/\text{ha} \\ \text{2035} &= 1.13 \quad \quad \quad \text{for VOB30} > 250 \text{ m}^3/\text{ha} \end{aligned}$$

2036 See Box 2.2.7 for a demonstration of the use of the VEF correction factor and BCEF to
2037 estimate biomass density.

Box 2.2.7: Use of volume expansion factor (VEF) and biomass conversion and expansion factor (BCEF)

Tropical broadleaf forest with a VOB30 = 100 m³/ha

First: Calculate the VEF
= Exp {1.300 - 0.209*Ln(100)} = 1.40

Second: Calculate VOB10
= 100 m³/ha x 1.40 = 140 m³/ha

Third: Take the BCEF from the table above
= Tropical hardwood with growing stock of 140 m³/ha = 1.3

Fourth: Calculate aboveground biomass density
= 1.3 x 140
= 182 t/ha

Data from scientific studies

2051 Scientific evaluations of biomass, volume or carbon stock are conducted under multiple
2052 motivations that may or may not align with the stratum-based approach required for
2053 deforestation and degradation assessments.

2054 Scientific plots may be used to represent the carbon stock of a stratum as long as there
2055 are multiple plots and the plots are randomly located. Many scientific plots will be in old
2056 growth forest and may provide a good representation of this stratum.

2057 The acceptable level of uncertainty will be defined in the political arena, but quality of
2058 research data could be illustrated by an uncertainty level of 20% or less (95%
2059 confidence equal to 20% of the mean or less). If this level is reached then these data
2060 could be applicable.

2.2.5.2.3 Step 3: Collect missing data

2062 It is likely that even if data exist they will not cover all strata so in almost all situations a
2063 new measuring and monitoring plan will need to be designed and implemented to
2064 achieve a Tier 2 level. With careful planning this need not be an overly costly
2065 proposition.

2066 The first step would be a decision on how many strata with deforestation or degradation
2067 in the reference period are at risk of deforestation or degradation in the future but do
2068 not have estimates of carbon stock. These strata should then be the focus of any future
2069 monitoring plan. Many resources are available or becoming available to assist countries

2070 in planning and implementing the collection of new data to enable them to estimate
2071 forest carbon stocks with high confidence (e.g. bilateral and multilateral organizations,
2072 FAO etc.), sources of such information and guidance is given in Box 2.2.8).

2073 **Box 2.2.8: Guidance on collecting new carbon stock data**

2074 Many resources are available to countries and organizations seeking to conduct
2075 carbon assessments of land use strata.

2076 The Food and Agriculture Organization of the United Nations has been supporting
2077 forest inventories for more than 50 years—data from these inventories can be
2078 converted to C stocks readily using the methods given above. However, it would
2079 be useful in the implementation of new inventories that instead of using plot less
2080 approach for measuring trees that the actual dbh be measured and recorded.
2081 Application of allometric equations commonly acceptable in carbon studies²⁵ to
2082 such data (by plots) would provide estimates of carbon stocks with lower
2083 uncertainty than estimates based on converting volume data as described above.
2084 The FAO National Forest Inventory Field Manual is available at:

2085 <http://www.fao.org/docrep/008/ae578e00.htm>

2086 Specific guidance on field measurement of carbon stocks can be found in Chapter
2087 4.3 of GPG LULUCF and also in the World Bank Sourcebook for Land Use, Land-Use
2088 Change and Forestry (available at:

2089 http://carbonfinance.org/doc/LULUCF_sourcebook_compressed.pdf)

2090 Lacking in the sources given in Box 2.2.9 is guidance on how to improve the estimates of
2091 the total impacts on forest carbon stocks from degradation, particularly from various
2092 intensities of selective logging (whether legal or illegal). The AFOLU guidelines consider
2093 losses from the actual trees logged, but does not include losses from damage to residual
2094 trees nor from the construction of skid trails, roads and logging decks; gains from
2095 regrowth are included but with limited guidance on how to apply the regrowth factors.
2096 An outline of the steps needed to improve the estimates of carbon emissions from
2097 selective logging are described in Box 2.2.9.

2098

²⁵E.g. Chave, J., C. Andalo, S. Brown, M. A. Cairns, J. Q. Chambers, D. Eamus, H. Folster, F. Fromard, N. Higuchi, T. Kira, J.-P. Lescure, B. W. Nelson, H. Ogawa, H. Puig, B. Riera, T. Yamakura. 2005. Tree allometry and improved estimation of carbon stocks and balance in tropical forests. *Oecologia* 145: 87-99.

2099

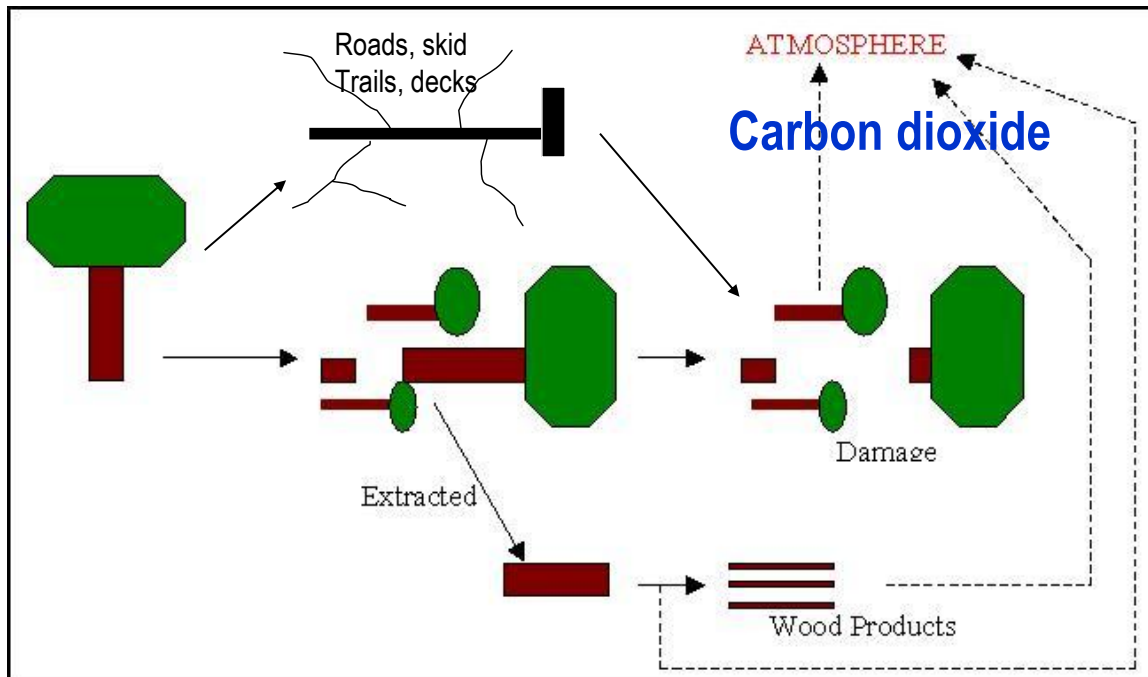
2100

2101

2102

Box 2.2.9: Estimating carbon gains and losses from logging

A model that illustrates the fate of live biomass and subsequent CO₂ emissions when a forest is selectively logged is shown below.



2103

2104

The total annual carbon emissions is a function of: (i) the area logged in a given year; (ii) the amount of timber extracted per unit area per year; (iii) the amount of dead wood produced in a given year (from tops and stump of the harvested tree, mortality of the surrounding trees caused by the logging, and tree mortality from the skid trails, roads, and logging decks) adjusted for decomposition, and (iv) the biomass that went into long term storage as wood products²⁶.

In equation form, the carbon impact of logging per unit area per year can be summed up as follows:

$$C \text{ Impact} = \Delta C_{\text{livebiomas}} + \Delta C_{\text{deadbiomas}} + \Delta C_{\text{woodproducts}}$$

Eq. (1)

2113

This equation is further described as follows:

$$(1) \quad \Delta C_{\text{livebiomas}} = \Delta C_{\text{live,loggingdamage}} + \Delta C_{\text{timberextraction}} + \Delta C_{\text{regrowthfactor}}$$

The change in biomass C caused by logging damage to live trees (tops, stump, surrounding trees, trees killed from putting in skid trails, roads, decks) and timber extracted reduces the carbon stock of live biomass (data which are best collected

2118

²⁶ Brown S, M Burnham, M Delaney, R Vaca, M Powell, A. Moreno. 2000. Issues and challenges for forest-based carbon-offset projects: a case study of the Noel Kempff Climate Action Project in Bolivia. *Mitigation and Adaptation Strategies for Climate Change* 5:99-121.

Brown, S., Pearson, T., Moore, N., Parveen, A., Ambagis, S. and Shoch D. 2005. Deliverable 6: Impact of logging on carbon stocks of forests: Republic of Congo as a case study. Report submitted to the United States Agency for International Development; Cooperative Agreement No. EEM-A-00-03-00006-00. Available from carbonservices@winrock.org

2119 from active logging concessions). The regrowth factor or rate accounts for a gain in
2120 carbon resulting from the regeneration of new trees to fill the gap and potential
2121 enhanced growth of residual trees. The regrowth rate can only be applied to the
2122 area of gaps and a relatively narrow zone extending into the forest around the gap
2123 that would likely benefit from additional light and not to the total area under
2124 logging. The quantities in (1) above can be expressed on an area basis (i.e., t
2125 C/ha) or on a m³ of extracted timber per ha.

2126 (2) $\Delta C_{deadbiomas} = \Delta C_{dead,loggingdamage} \times WoodDecompositionFactor$

2127 In areas undergoing selective logging, dead wood cannot be ignored because
2128 logging increases the size of this pool. The change in the dead wood pool should
2129 be estimated to account for decomposition that occurs over time. Research has
2130 shown that dead wood decomposes relatively slowly in tropical forests and hence
2131 this pool has a long turnover time. The damaged wood is assumed to enter the
2132 dead wood pool, where it starts to decompose, and each year more dead wood is
2133 added from harvesting, but each year some is lost because of decomposition and
2134 resulting emissions of carbon. Decomposition of dead wood is modeled as a simple
2135 exponential function based on mass of dead wood and a decomposition coefficient
2136 (proportion decomposed per year that can range from about <0.05 to 0.15 per
2137 year).

2138 (3) $\Delta C_{woodproducts} = \Delta C_{timberextraction} \times proportion_{woodproducts}$

2139 Not all of the decrease in live biomass due to logging is emitted to the atmosphere
2140 as a carbon emission because a relatively large fraction of the harvested wood
2141 goes into long term wood products. However, even wood products are not a
2142 permanent storage of carbon—some of it goes into products that have short lives
2143 (some paper products), some turns over very slowly (e.g. construction timber and
2144 furniture), but all is eventually disposed of by burning, decomposition or buried in
2145 landfills.

2146 In addition to quantifying the changes in Eq. 1, two other pieces of information are
2147 needed to fully estimate the total net emissions of CO₂—these are the amount of
2148 timber extracted per unit area per year and the total area logged per year. Total
2149 emissions are then estimated as the product of total change in carbon stocks (from
2150 Eq.1), the timber extraction rate and the total area logged.

2151 **Creating a national look-up table**

2152 A cost-effective method for Approach A and Approach B stratifications may be to create
2153 a “national look-up table” for the country that will detail the carbon stock in each
2154 selected pool in each stratum. Look-up tables should ideally be updated periodically to
2155 account for changing mean biomass stocks due to shifts in age distributions, climate,
2156 and or disturbance regimes. The look up table can then be used through time to detail
2157 the pre-deforestation or degradation stocks and estimated stocks after deforestation and
2158 degradation. An example is given in Box 2.2.10.

2159

2160

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Box 2.2.10: A national look up table for deforestation and degradation

2162

The following is a hypothetical look-up table for use with approach A or approach B stratification. We can assume that remote sensing analysis reveals that 800 ha of lowland forest were deforested to shifting agriculture and 500 ha of montane forest were degraded. Using the national look-up table results in the following:

2163

2164

2165

2166

The loss for deforestation would be

2167

$$154 \text{ t C/ha} - 37 \text{ t C/ha} = 117 \text{ t C/ha} \times 800 \text{ ha} = 93,600 \text{ t C.}$$

2168

The loss for the degradation would be

2169

$$130 \text{ t C/ha} - 92 \text{ t C/ha} = 38 \text{ t C/ha} \times 500 \text{ ha} = 19,000 \text{ t C}$$

2170

(Note that degradation will often have been caused by harvest and therefore emissions will be decreased if storage in long-term wood products, rather than by fuelwood extraction, was included—that is the harvested wood did not enter the atmosphere.)

2171

2172

2173

Stratum	Aboveground Tree	Belowground Tree	Dead wood	Non-Tree	Total
Lowland Forest	110	23	18	3	154
Montane Forest	91	17	17	5	130
Open Woodland	48	10	6	8	72
Degraded Lowland Forest	70	15	18	4	107
Degraded Montane Forest	58	11	16	7	92
Degraded Woodland	28	6	6	6	46
Shifting Cultivation	20	5	5	7	37
Permanent Agriculture	0	0	0	4	4

2174

2175

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2177

2178 **2.3 ESTIMATION OF SOIL CARBON STOCKS**

2179 Tim Pearson, Winrock International, USA

2180 Nancy Harris, Winrock International, USA

2181 David Shoch, The Nature Conservancy, USA

2182 Sandra Brown, Winrock International, USA

2183

2184 Florian Siegert, University of Munich, Germany

2185 Hans Joosten, Wetlands International, The Netherlands

2186 **2.3.1 Scope of chapter**

2187 **Chapter 2.3 presents guidance on the estimation of the organic carbon**
2188 **component of soil of the forests being deforested and degraded. Guidance is**
2189 **provided on: (i) which of the three IPCC Tiers to be used, (ii) potential methods**
2190 **for the stratification by Carbon Stock of a country's forests and (iii) actual**
2191 **Estimation of Carbon Stocks of Forests Undergoing Change.**

2192 IPCC AFOLU divides soil carbon into three pools: mineral soil organic carbon, organic soil
2193 carbon, and mineral soil inorganic carbon. The focus in this section will be on only the
2194 organic carbon component of soil.

2195

2196 In **Section 2.3.2** explanation is provided on IPCC Tiers for soil carbon estimates.

2197 In **Section 2.3.3** the focus is on how to generate a good Tier 2 analysis for soil carbon.

2198 In **Section 2.2.4** guidance is given on the estimation of emissions as a result of land use
2199 change in peat swamp forests.

2200

2201 **2.3.2 Explanation of IPCC Tiers for soil carbon estimates**

2202 For estimating emissions from organic carbon in mineral soils, the IPCC AFOLU
2203 recommends the stock change approach but for organic carbon in organic soils such as
2204 peats, an emission factor approach is used (Table 4.5). For mineral soil organic carbon,
2205 departures in carbon stocks from a reference or base condition are calculated by
2206 applying stock change factors (specific to land-use, management practices, and inputs
2207 [e.g. soil amendment, irrigation, etc.]), equal to the carbon stock in the altered condition
2208 as a proportion of the reference carbon stock. Tier 1 assumes that a change to a new
2209 equilibrium stock occurs at a constant rate over a 20 year time period. Tiers 2 and 3
2210 may vary these assumptions, in terms of the length of time over which change takes
2211 place, and in terms of how annual rates vary within that period. Tier 1 assumes that the
2212 maximum depth beyond which change in soil carbon stocks should not occur is 30 cm;
2213 Tiers 2 and 3 may lower this threshold to a greater depth.

2214 Tier 1 further assumes that there is no change in mineral soil carbon in forests remaining
2215 forests. Hence, estimates of the changes in mineral soil carbon could be made for
2216 deforestation but are not needed for degradation. Tiers 2 and 3 allow this assumption to
2217 change. In the case of degradation, the Tier 2 and 3 approaches are only recommended
2218 for intensive practices that involve significant soil disturbance, not typically encountered
2219 in selective logging. In contrast, selective logging of forests growing on organic carbon

2220 soils such as the peat-swamp forests of South East Asia could result in large emissions
 2221 caused by practices such as draining to remove the logs from the forest (see Section
 2222 2.3.3 for further details on this topic).

2223 **Table 2.3.1: IPCC guidelines on data and/or analytical needs for the different**
 2224 **Tiers for soil carbon changes in deforested areas.**

Soil carbon pool	Tier 1	Tier 2	Tier 3
Organic carbon in mineral soil	Default reference C stocks and stock change factors from IPCC	Country-specific data on reference C stocks & stock change factors	Validated model or direct measures of stock change through monitoring networks
Organic carbon in organic soil	Default emission factor from IPCC	Country-specific data on emission factors	Validated model or direct measures of stock change

2225
 2226 Variability in soil carbon stocks can be large; Tier 1 reference stock estimates have
 2227 associated uncertainty of up to +/- 90%. Therefore it is clear that if soil is a key
 2228 category, Tier 1 estimates should be avoided.

2229 **2.3.3 When and how to generate a good Tier 2 analysis for soil**
 2230 **carbon**

2231 Modifying Tier 1 assumptions and replacing default reference stock and stock change
 2232 estimates with country-specific values through Tier 2 methods is recommended to
 2233 reduce uncertainty for significant sources. Tier 2 provides the option of using a
 2234 combination of country-specific data and IPCC default values that allows a country to
 2235 more efficiently allocate its limited resources in the development of emission inventories.

2236 How can one decide if loss of soil C during deforestation is a significant source? It is
 2237 recommended that, where emissions from soil carbon are likely to represent a key
 2238 subcategory of overall emissions from deforestation—that is > 25-30%, the emissions
 2239 accounting should move from a Tier 1 to a Tier 2 approach for estimating carbon
 2240 emissions from soil. Generally speaking, where reference soil carbon stocks equal or
 2241 exceed aboveground biomass carbon, carbon emissions from soil often exceed 25% of
 2242 total emissions from deforestation upon conversion to cropland, and consideration should
 2243 be given to applying a Tier 2 approach to estimating emissions from soil carbon. If
 2244 deforestation in an area commonly converts forests to other land uses such as pasture or
 2245 other perennial crops, then the loss of soil carbon and resulting emissions is unlikely to
 2246 reach 25%, and thus a Tier 1 approach would suffice.

2247 Assessments of opportunities to improve on Tier 1 assumptions with a Tier 2 approach
 2248 are summarized in Table 2.3.2.

2249

2250

2251

2252

Table 2.3.2: Opportunities to improve on Tier 1 assumptions using a Tier 2 approach.

	Tier 1 assumptions	Tier 2 options	Recommendation
Depth to which change in stock is reported	30 cm	May report changes to deeper depths	Not recommended. There is seldom any benefit in sampling to deeper depths for tropical forest soils because impacts of land conversion and management on soil carbon tend to diminish with depth - most change takes place in the top 25-30 cm.
Time until new equilibrium stock is reached	20 years	May vary the length of time until new equilibrium is achieved, referencing country-specific chronosequences or long-term studies	Recommended where a chronosequence ²⁷ or long-term study data are available. Some soils may reach equilibrium in as little as 5-10 years after conversion, particularly in the humid tropics ²⁸ .
Rate of change in stock	Linear	May use non-linear models	Not recommended – best modeled with Tier 3-type approaches. As well, a typical 5-year reporting interval effectively “linearizes” a non-linear model and would undo the benefits of a model with finer resolution of varying annual changes.
Reference stocks	IPCC defaults	Develop country-specific reference stocks consulting other available databases or consolidating country soil data from existing sources (universities, agricultural extension services, etc.).	IPCC defaults comprehensive. Not recommended unless country-specific data are available.
Stock change factors	IPCC defaults	Develop country-specific stock change factors from chronosequence or long-term study.	IPCC defaults fairly comprehensive. Not recommended unless significant areas (that can be delineated spatially) are represented by drainage as a typical conversion practice.

2253

²⁷ A chronosequence is a series on land units that represent a range of ages after some event – they are often used to substitute time with space, e.g. a series of cropfield of various ages since they were cleared from forests (making sure they are on same soil type, slope, etc.).

²⁸ Detwiler, R. P. 1986. Land use change and the global carbon cycle: the role of tropical soils. *Biogeochemistry* 31: 1-14.

2254 The IPCC default values for reference soil carbon stocks and stock change factors are
2255 comprehensive and reflect the most recent review of changes in soil carbon with
2256 conversion of native soils. Reference stocks and stock change factors represent average
2257 conditions globally, which means that, in at least half of the cases, use of a more
2258 accurate and precise (higher Tier) approach will not produce a higher estimate of stocks
2259 or emissions than the Tier 1 defaults with respect to the categories covered.

2260 Where country-specific data are available from existing sources, Tier 2 reference stocks
2261 should be constructed to replace IPCC default values. Measurements or estimates of soil
2262 carbon can be acquired through consultations with local universities, agricultural
2263 departments or extension agencies, all of which often carry out soil surveying at scales
2264 suited to deriving national or regional level estimates. It should be acknowledged
2265 however that because agricultural extension work is targeted to altered (cultivated)
2266 sites, agricultural extension agencies may have comparatively little information gathered
2267 on reference soils under native vegetation. Where data on reference sites are available,
2268 it would be advantageous if the soil carbon measurements were geo-referenced. Soil
2269 carbon data generated through typical agricultural extension work is often limited to
2270 carbon concentrations (i.e. percent carbon) only, and for this information to be usable,
2271 carbon concentrations must be paired with soil bulk density (mass per unit volume),
2272 volume of fragments > 2 mm, and depth sampled to derive a mass C per unit area of
2273 land surface (see Ch. 4.3 of the IPCC GPG report for more details about soil samples).

2274 A spatially-explicit global database of soil carbon is also available from which country-
2275 specific estimates of reference stocks can be sourced. The ISRIC World Inventory of Soil
2276 Emission (WISE) Potential Database offers 5 x 5 minute grid resolution of soil organic
2277 carbon content and bulk density to 30 cm depth, and can be accessed online at:

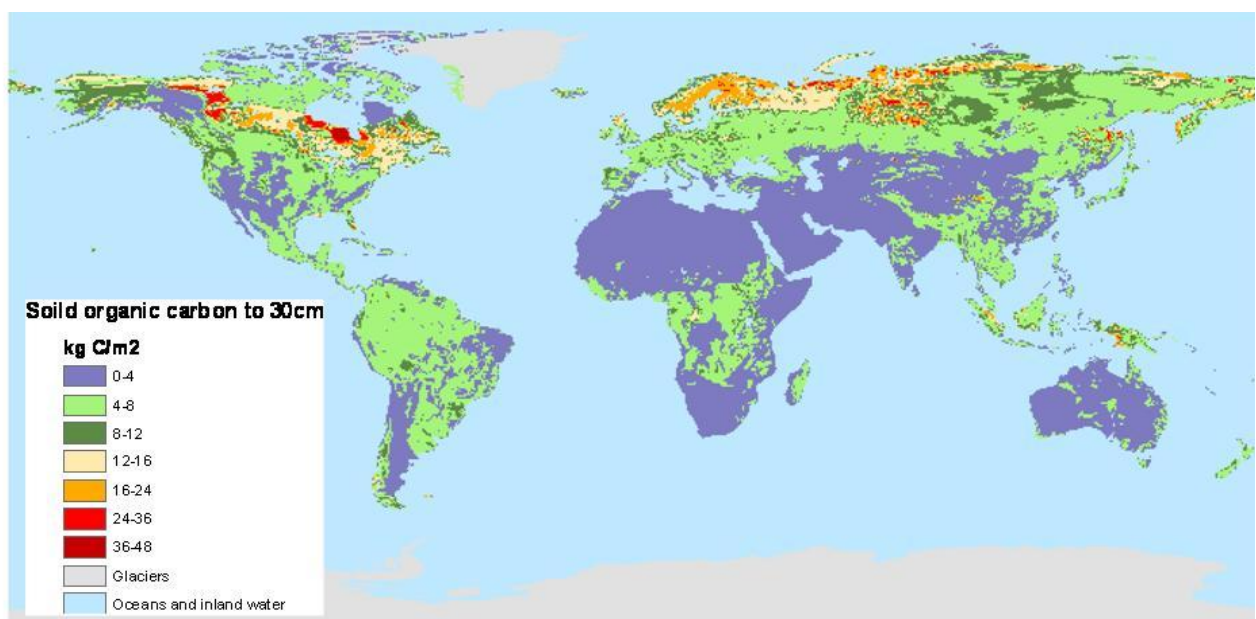
2278 <http://www.isric.org/UK/About+Soils/Soil+data/Geographic+data/Global/WISE5by5minutes.htm>

2279

2280 A soil carbon map is also available from the US Department of Agriculture, Natural
2281 Resources Conservation Service (Figure 2.3.1). This map is based on a reclassification of
2282 the FAO-UNESCO Soil Map of the World combined with a soil climate map. This map
2283 shows is little variation for soil C in the tropics with most areas showing a range in soil
2284 carbon of 40-80 t C/ha (4-8 Kg C/m²). The soil organic carbon map shows the
2285 distribution of the soil organic carbon to 30 cm depth, and can be downloaded from:

2286 ftp://www.daac.ornl.gov/data/global_soil/IsricWiseGrids/

2287 **Figure 2.3.1: Soil organic carbon map** (kg/m² or x10 t/ha; to 30 cm depth) from the
2288 global map produced by the USDA Natural Resources Conservation Service.



2289

2290 Existing map sources can be useful to countries for developing estimates for the
2291 reference emission period and for assisting in determining whether changes in soil
2292 carbon stocks after deforestation would be a key category or not. Deforestation could
2293 emit up to 30-40% of the carbon stock in the top 30 cm of soil during the first 5 years or
2294 so after clearing in the humid tropics. Using the soil map above and assuming the soil C
2295 content to 30 cm is 80 t C/ha, a 40% emission rate would result in 32 t C/ha being
2296 emitted in the first 5 years. If the carbon stock of the forest vegetation was 120 t C/ha
2297 (not unreasonable), then the emission of 32 t C/ha is more than 25% of the C stock in
2298 forest vegetation and could be considered a significant emissions source.

2299 There are two factors not included in the IPCC defaults that can potentially influence
2300 carbon stock changes in soils: soil texture and soil moisture. Soil texture has an
2301 acknowledged effect on soil organic carbon stocks, with coarse sandy soils (e.g.
2302 spodosols) having lower carbon stocks in general than finer texture soils such as loams
2303 or clayey soils. Thus the texture of the soil is a useful indicator to determine the likely
2304 quantity of carbon in the soil and the likely amount emitted as CO₂ upon conversion. A
2305 global data set on soil texture is available for free downloading and could be used as an
2306 indicator of the likely soil carbon content²⁹. Specifically, soil carbon in coarse sandy
2307 soils, with less capacity for soil organic matter retention, is expected to oxidize more
2308 rapidly and possibly to a greater degree than in finer soils. However, because coarser
2309 soils also tend to have lower initial (reference) soil carbon stocks, conversion of these
2310 soils is unlikely to be a significant source of emissions and therefore development of a
2311 soil texture-specific stock change factor is not recommended for these soils.

2312 Drainage of a previously inundated mineral soil increases decomposition of soil organic
2313 matter, just as it does in organic soils, and unlike the effect of soil texture, is likely to be
2314 associated with high reference soil carbon stocks. These are reflected in the IPCC default
2315 reference stocks for forests growing on wetland soils, such as floodplain forests.
2316 Drainage of forested wetland soils in combination with deforestation can thus represent a
2317 significant source of emissions. Because this factor is lacking from the IPCC default stock
2318 change factors, its effects would not be discerned using a Tier 1 approach. In other
2319 words, IPCC default stock change factors would underestimate soil carbon emissions
2320 where deforestation followed by drainage of previously inundated soils occurred. Where
2321 drainage practices on wetland soils are representative of national trends and significant
2322 areas, and for which spatial data are available, the Tier 2 approach of deriving a new,
2323 country-specific stock change factor from chronosequences or long-term studies is
2324 recommended.

2325 Field measurements can be used to construct chronosequences that represent changes
2326 in land cover and use, management or carbon inputs, from which new stock change
2327 factors can be calculated, and many sources of methods are available (see Box 4.9).
2328 Alternatively, stock change factors can be derived from long-term studies that report
2329 measurements collected repeatedly over time at sites where land-use conversion has
2330 occurred. Ideally, multiple paired comparisons or long-term studies would be done over
2331 a geographic range comparable to that over which a resulting stock change factor will be
2332 applied, though they do not require representative sampling as in the development of
2333 average reference stock values.

2334

²⁹ Webb, R. W., C. E. Rosenzweig, and E. R. Levine. 2000. Global Soil Texture and Derived Water-Holding Capacities (Webb et al.). Data set. Available on-line [<http://www.daac.ornl.gov>] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. doi:10.3334/ORNLDAAC/548.

2335 **2.3.4 Emissions as a result of land use change in peat swamp**
2336 **forests**

2337

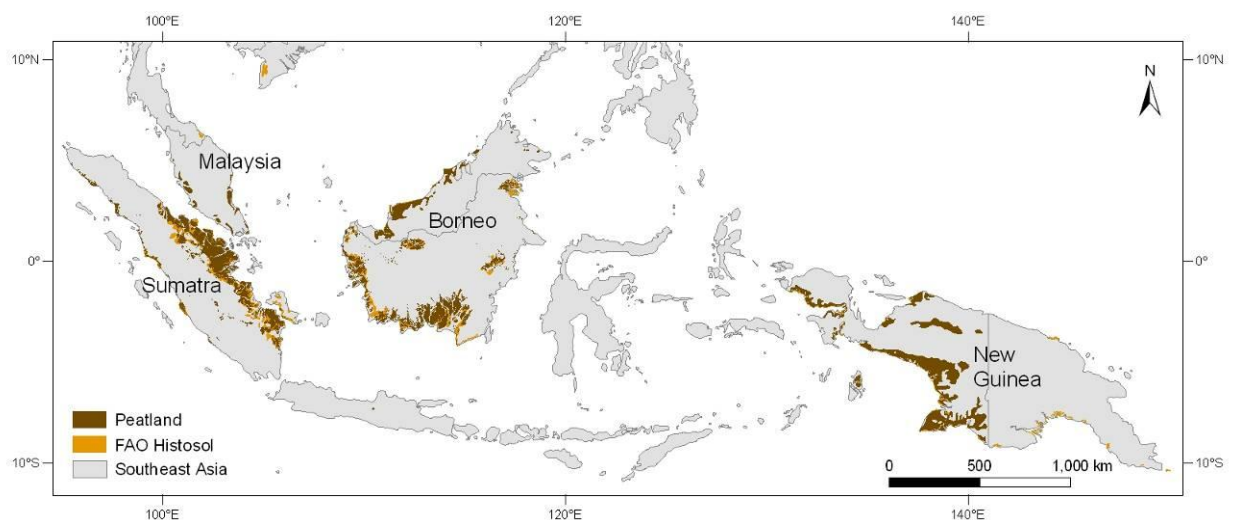
2338 Deforestation of peat swamp forests (on organic soils) represents a special case and
2339 guidance is given in this section.

2340 Tropical peatlands occupy about 10% of the global peatland area, approximately 65% of
2341 the global area of tropical peatland occur in Southeast Asia (Figure A). Peat is a dead
2342 organic matter occurring largely in poorly draining environments. It forms at all altitudes
2343 and climates. In the tropics, peat is largely formed from tree and root remnants and
2344 accumulates to deposits in depths up to 20 meters. If a tropical peat deposit is 10
2345 meters thick it contains over 5,000 t/ha carbon, more than 25-fold more than that of the
2346 forest biomass growing above ground. In its natural state, tropical peatland may
2347 sequester huge amounts of carbon. Sequestration results when the rate of
2348 photosynthesis is larger than decomposition. Carbon sequestration range in average
2349 from 0.12-0.74 t C/ha/yr. Compared to boreal peatlands, the tropical rate is up to 4
2350 times higher. If tropical peat is drained for agriculture or plantations it quickly
2351 decomposes due to bacterial activity, resulting in huge emissions of CO₂ and N₂O to the
2352 atmosphere.

2353 A global map indicating peat is available from FAO (FAO-UNESCO Soil Map of the World).
2354 Wetlands International has published detailed maps on the distribution of peatland and
2355 below ground carbon for Sumatra, Kalimantan and West Papua based on maps, land
2356 surveys and satellite imagery³⁰.

2357

2358 **Figure 2.3.2: Extent of lowland peat forests in Southeast Asia.** The Wetlands
2359 International data have higher spatial detail and hence accuracy than the FAO data.



2360

2361

2362 Tier 2 and 3 methods require detailed knowledge on peat carbon stock and estimation of
2363 emission requires detailed knowledge of the proportion of emissions from drainage and
2364 fire. Useful emissions factors (EF) for calculating peatland carbon emissions for REDD

³⁰ Wetlands International 2007. http://www.wetlands.or.id/publications_maps.php

2365 must be site-specific; a recent literature review questions the accuracy and usefulness of
2366 existing EF Tier 1 for operational use. Long term measurements or well established
2367 proxies must be put in place to support Tier 2 and 3 methodologies. Countries with
2368 significant peatland forest should develop adapted domestic data to estimate and report
2369 the carbon stock changes and non- CO₂ emissions resulting from land use and land use
2370 changes.

2371 There is a large uncertainty of the extent of tropical peatlands in Southeast Asia and
2372 worldwide. Current estimates of the peatland area in Malaysia and Indonesia vary from
2373 21 - 27 million ha. This large range results from the difficulty of accessing the remote
2374 terrain to carry out ground surveys. Improved assessments of peatland extent will
2375 require high resolution satellite remote sensing combined with field sampling as peat
2376 swamp forests may not be well discriminated from forests on mineral soil since both can
2377 support forest of similar structure. The same is true if peatlands have been deforested
2378 by recurrent fire or converted into plantations or agricultural land. The evaluation of
2379 historical satellite imagery may help to identify disturbed or converted peatland.
2380 Traditional methods to assess peat type and volume are labor intensive and thus time
2381 consuming; new technologies reduce the time required for measurement and increase
2382 the spatial accuracy, but are expensive and require specialized skills. Peat depth can be
2383 only assessed by field sampling using manual peat corers or geo-electrical
2384 measurements. Both methods are tedious to perform over larger areas due to the
2385 difficult terrain in peat swamps. Knowledge on the 3D topology of the peat dome is
2386 important for hydrology and modeling. New technologies such as airborne LIDAR
2387 measurements combined with ortho aerial photographs allow assessing above ground
2388 peat dome topography and peat burn depth in the case of fire. A recent study based on
2389 such methods estimates peat deposits of Indonesia to be larger than 50 Gt C³¹.

2390 In the past two decades large areas of peat forests in Southeast Asia have been
2391 destroyed by logging, drainage and fire. Compared to the aboveground emissions that
2392 result from clearing the forest vegetation, emissions from peat are significantly larger in
2393 case of fire and continue through time because drainage causes a lowering of the water
2394 table, allowing biological oxidation of the peat (Figure 2.3.3). Both processes cause
2395 significant emissions of GHG gases. Although the area of tropical peatlands in Indonesia
2396 is only about 1.5% that of the global land surface, uncontrolled burning of peat there in
2397 1997 emitted 2,0-3,5 Gt CO₂ equivalent to some 10% of global fossil fuel emissions for
2398 the same year³². Emission estimates from peat fires require Tier3 and currently have
2399 great uncertainties, because:

- 2400 • Various gases and compounds and relative fractions of these will be emitted
- 2401 depending on fire severity, water table, peat moisture and peat type
- 2402 • the combusted peat volume depends on water table and peat moisture
- 2403 • Fire intensity and burn depth depend on land cover type and previous fire history.

2404

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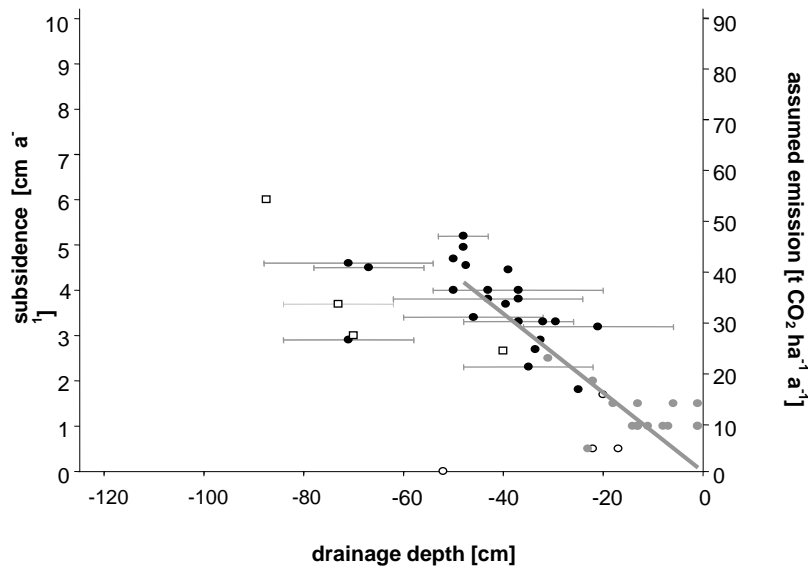
2407

³¹ Jaenicke, J., J.O. Rieley, C. Mott, P. Kimman, F. Siegert (2008). Determination of the amount of carbon stored in Indonesian peatlands. *Geoderma* 147: 151–158

³² Page, S.E., Siegert, F., Rieley, J. O., Boehm, H.D.V., Jayak, A., & S. Limin (2002). The amount of carbon released from peat and forest fires in Indonesia during 1997. *Nature* 420:61-65.

van der Werf G. R., J. T. Randerson, G. J. Collatz, L. Giglio, P. S. Kasibhatla, A. F. Arellano, Jr., S. C. Olsen, E. S. Kasischke (2004). Continental-Scale Partitioning of Fire Emissions During the 1997 to 2001 El Niño/La Niña Period. *Science* 303: 73 - 76

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2411

2412 **Figure 2.3.3: Relation between drainage depth and CO₂ emissions from peat**
2413 **decomposition in tropical peat swamps.** Source: Couwenberg et al., in press.

2414 Rate of subsidence in relation to mean annual water level below surface. Horizontal bars indicate
2415 standard deviation in water table (where available). Open circles denote unused, drained forested
2416 sites. Land use: (□) agriculture, (●) oil palm (recorded 13 to 16 or 18 to 21 years after drainage),
2417 (●) degraded open land in the Ex Mega Rice Project area, recorded ~10 to ~12 years after
2418 drainage, (○) drained forested plots, recorded ~10 to 12 years after drainage.

2419

2420

2421 Reliable emissions factors are essential for reliably estimating fire emissions. The IPCC
2422 guidelines provide limited guidance for estimating GHG emissions from peat fires,
2423 because peat fires are different from forest fires due to oxygen limitation and the
2424 smoldering nature of combustion. Burn history and land cover can quite easily be
2425 measured by satellite remote sensing. Burn depth assessment requires field and/or
2426 LIDAR measurements and the determination of gas composition requires laboratory
2427 combustion experiments and field measurements. The depth of the water table and
2428 moisture content are key variables that control both bacterial decomposition and fire risk
2429 and have to be accurately measured and monitored in dip wells to estimate emissions.

2430 Over time GHG emissions by biological oxidation of peat are also significant. Emissions of
2431 CO₂ via oxidation begin when either the peat swamp forest is removed and/or the water
2432 table is lowered due to drainage for agriculture or logging purposes. Most carbon is
2433 released in the form of CO₂ in an aerobic layer near the surface by microbial
2434 decomposition of fossil plant material. Suitable long term measurements of at least a
2435 year are required to assess emission rates under differing water management regimes.
2436 Very few such measures exist today. A recent review showed that cleared and drained
2437 peatlands emit in the range of 9 CO₂ t/ha/yr for each 10 cm of additional drainage
2438 depth³³. If the water table is lowered by of 0.4 meters by draining, CO₂ emissions are

³³ Couwenberg J., Dommain R. & H. Joosten (2009). Greenhouse gas fluxes from tropical peatlands in Southeast Asia Running title: Greenhouse gas fluxes from tropical peatlands. Global Change Biology, in press

2439 estimated at 35 tons per hectare per year. (Figure 2.3.3). It was estimated that in 10
2440 years up to 20 Gt CO₂ could have been released from Indonesia's peatland as a result of
2441 peat decomposition and oxidation, from land use, land use change and fire (conversion
2442 to farmland and plantations)³⁴. Two important non-CO₂ greenhouse gases produced by
2443 organic matter decomposition are methane CH₄ and nitrous oxide N₂O with the latter
2444 more important due to its large global warming potential. Emissions from tropical peats
2445 are low compared to CO₂, but evidence suggests that N₂O, emissions increase following
2446 land use change and drainage. The determination of GHG emission factors for drained
2447 peat require rigorous flux measurements by chambers or eddy covariance
2448 measurements in combination with continuous monitoring of site conditions.

2449 GHG releases have been accelerating in the past two decades due to a fast economic
2450 development in SE Asia. Large areas have been converted into oil palm and pulp wood
2451 plantations, with annual losses of peat swamp forest estimated at more than 2%
2452 annually. For example Riau province in central Sumatra has lost 65 per cent of its forests
2453 over the last 25 years. A wall-to-wall study by WWF found that deforestation of nearly 4
2454 million ha of tropical forests including 1.8m ha peat swamp forest may have generated
2455 the release of up to 3.6 gigatons of carbon dioxide including emissions from
2456 deforestation and decomposition and burning of peat³⁵.

2457 The role of tropical peat is crucial in terms of GHG emissions because the carbon stock of
2458 peat considerably outweighs that of the biomass above ground. Moreover significant
2459 amounts of carbon are released by fire and bacterial decomposition. Both fire and
2460 decomposition processes need to be considered when estimating emissions from carbon.
2461 Fire is an instantaneous release of carbon that takes place one or more times, but
2462 decomposition occurs over a long timeframe (many years). Decomposition rates are
2463 quite low, but because they are continually occurring over long periods following
2464 drainage, they sum up to huge releases of carbon.

2465

2466

2467

³⁴ Hooijer, A., Silvius, M., Wösten, H. and Page, S. (2006). PEAT-CO₂, Assessment of CO₂ emissions from drained peatlands in SE Asia. Delft Hydraulics report Q3943

³⁵ WWF, 2008. Deforestation, Forest Degradation, Biodiversity Loss, and CO₂ Emissions in Riau, Sumatra, Indonesia. WWF Indonesia Technical Report. February 27, 2008.

2468

2469 **2.4 METHODS FOR ESTIMATING CO₂ EMISSIONS FROM** 2470 **DEFORESTATION AND FOREST DEGRADATION**

2471 Sandra Brown, Winrock International, USA

2472 Barbara Braatz, USA

2473 **2.4.1 Scope of this Chapter**

2474 This chapter describes the methodologies that can be used to estimate carbon emissions
2475 from deforestation and forest degradation. It builds on Chapters 2.1, 2.2 and 2.3 of this
2476 Sourcebook, which describe procedures for collecting the input data for these
2477 methodologies, namely areas of land use and land-use change (Chapter 2.1), and carbon
2478 stocks and changes in carbon stocks (Chapters 2.2 and 2.3).

2479 The methodologies described here are derived from the 2006 IPCC AFOLU Guidelines and
2480 the 2003 IPCC GPG-LULUCF, and focus on the Tier 2 IPCC methods, as these require
2481 country-specific data but do not require expertise in complex models or detailed national
2482 forest inventories.

2483 The AFOLU Guidelines and GPG-LULUCF define six categories of land use³⁶ that are
2484 further sub-divided into subcategories of land remaining in the same category (e.g.,
2485 Forest Land Remaining Forest Land) and of land converted from one category to another
2486 (e.g., Land converted to Cropland). The land conversion subcategories are then divided
2487 further based on initial land use (e.g., Forest Land converted to Cropland, Grassland
2488 converted to Cropland). This structure was designed to be broad enough to classify all
2489 land areas in each country and to accommodate different land classification systems
2490 among countries. The structure allows countries to account for, and track over time,
2491 their entire land area, and enables greenhouse gas estimation and reporting to be
2492 consistent and comparable among countries. For REDD estimation, each subcategory
2493 could be further subdivided by climatic, ecological, soils, and/or anthropogenic
2494 disturbance factors, depending upon the level of stratification chosen for area change
2495 detection and carbon stock estimation (see Chapters 2.1, 2.2 and 2.3).

2496 For the purposes of this Sourcebook, five IPCC land-use subcategories are relevant.
2497 Although the term deforestation within the REDD mechanism remains to be defined, it is
2498 likely to be encompassed by the four land-use change subcategories defined for
2499 conversion of forests to non-forests (see Section 1.2.3³⁷). Forest degradation, or the
2500 long-term loss of carbon stocks that does not qualify as deforestation is encompassed by
2501 the IPCC land-use subcategory "Forest Land Remaining Forest Land." The methodologies
2502 that are presented here are based on the sections of the AFOLU Guidelines and the GPG-
2503 LULUCF that pertain to these land-use subcategories.

2504 Within each land-use subcategory, the IPCC methods track changes in carbon stocks in
2505 five pools (see Chapters 2.2 and 2.3). The IPCC emission/removal estimation
2506 methodologies cover all of these carbon pools. Total net carbon emissions equal the sum
2507 of emissions and removals for each pool. However, as is discussed in Chapter 4, REDD

³⁶ The names of these categories are a mixture of land-cover and land-use classes, but are collectively referred to as 'land-use' categories by the IPCC for convenience.

³⁷ The subcategory "Land Converted to Wetlands" includes the conversion of forest land to flooded land, but as this land-use change is unlikely to be important in the context of REDD accounting, and measurements of emissions from flooded forest lands are relatively scarce and highly variable, this land-use change is not addressed further in this chapter.

2508 accounting schemes may or may not include all carbon pools. Which pools to include will
 2509 depend on decisions by policy makers the could be driven by such factors as financial
 2510 resources, availability of existing data, ease and cost of measurement, and the principle
 2511 of conservativeness.

2512 **2.4.2 Linkage to 2006 IPCC Guidelines**

2513 Table 2.4.1 lists the sections of the AFOLU Guidelines that describe carbon estimation
 2514 methods for each land-use subcategory. This table is provided to facilitate searching for
 2515 further information on these methods in the AFOLU Guidelines, which can be difficult
 2516 given the complex structure of this volume. To review greenhouse gas estimation
 2517 methods for a particular land-use category in the AFOLU Guidelines, one must refer to
 2518 two separate chapters: a generic methods chapter (Chapter 2) and the land-use
 2519 category chapter specific to that land-use category (i.e., either Chapter 4, 5, 6, 7, 8, or
 2520 9). The methods for a particular land-use subcategory are contained in sections in each
 2521 of these chapters.

2522 **Table 2.4.1: Locations of Carbon Estimation Methodologies in the 2006 AFOLU**
 2523 **Guidelines**

Land-Use Category (Relevant Land-Use Category Chapter in AFOLU Guidelines)	Land-Use Subcategory (Subcategory Acronym)	Sections in Relevant Land-Use Category Chapter (Chapter 4, 5, 6, 8, or 9)	Sections in Generic Methods Chapter (Chapter 2)
Forest Land (Chapter 4)	Forest Land	4.2.1	2.3.1.1
	Remaining Forest	4.2.2	2.3.2.1
	Land (FF)	4.2.3	2.3.3.1.
Cropland (Chapter 5)	Land Converted to Cropland (LC)	5.3.1	2.3.1.2
		5.3.2	2.3.2.2
		5.3.3	2.3.3.1
Grassland (Chapter 6)	Land Converted to Grassland (LG)	6.3.1	2.3.1.2
		6.3.2	2.3.2.2
		6.3.3	2.3.3.1
Settlements (Chapter 8)	Land Converted to Settlements (LS)	8.3.1	2.3.1.2
		8.3.2	2.3.2.2
		8.3.3	2.3.3.1
Other Land (Chapter 9)	Land Converted to Other Land (LO)	9.3.1	2.3.1.2
		9.3.2	2.3.2.2
		9.3.3	2.3.3.1

2524
 2525 Information and guidance on uncertainties relevant to estimation of emissions from land
 2526 use and land-use change are located in various chapters of two separate volumes of the
 2527 2006 IPCC Guidelines. Chapter 3 of the General Guidance and Reporting volume (Volume
 2528 1) of the 2006 IPCC Guidelines provides detailed, but non-sector-specific, guidance on
 2529 sources of uncertainty and uncertainty estimation methodologies. Land-use subcategory-
 2530 specific information about uncertainties for specific carbon pools and land uses is
 2531 provided in each of the land-use category chapters (i.e., Chapter 4, 5, 6, 7, 8, or 9) of
 2532 the AFOLU Guidelines (Volume 4).

2533 **2.4.3 Organization of this Chapter**

2534 The remainder of this chapter discusses carbon emission estimation for deforestation and
 2535 forest degradation:

2536

- 2537 □ **Section 2.4.4** addresses basic issues related to carbon estimation, including the
 2538 concept of carbon transfers among pools, emission units, and fundamental
 2539 methodologies for estimating annual changes in carbon stocks.
- 2540 □ **Section 2.4.5** describes methods for estimating carbon emissions from
 2541 deforestation based on the generic IPCC methods for land converted to a new
 2542 land-use category, and on the IPCC methods specific to types of land-use
 2543 conversions from forests.
- 2544 □ **Section 2.4.6** describes methods for estimating carbon emissions from forest
 2545 degradation based on the IPCC methods for “Forest Land Remaining Forest Land.”
 2546

2547 **2.4.4 Fundamental Carbon Estimating Issues**

2548 The overall carbon estimating method used here is one in which net changes in carbon
 2549 stocks in the five terrestrial carbon pools are tracked over time. For each strata or sub-
 2550 division of land area within a land-use category, the sum of carbon stock changes in all
 2551 the pools equals the total carbon stock change for that stratum. In the REDD context,
 2552 discussions center on gross emissions thus estimating the decrease in total carbon
 2553 stocks, which is equated with emissions of CO₂ to the atmosphere, is all that is needed
 2554 at this time. For deforestation at a Tier 1 level, this simply translates into the carbon
 2555 stock of the forest being deforested because it is assumed that this goes to zero when
 2556 deforested. However, a decrease in stocks in an individual pool may or may not
 2557 represent an emission to the atmosphere because an individual pool can change due to
 2558 both carbon transfers to and from the atmosphere, and carbon transfers to another pool
 2559 (e.g., the transfer of biomass to dead wood during logging). Disturbance matrices are
 2560 discussed below as a means to track carbon transfers among pools at higher Tier levels
 2561 and thereby avoid over- or underestimates of emissions and improve uncertainty
 2562 estimation.

2563 In the methods described here, all estimates of changes in carbon stocks (e.g., biomass
 2564 growth, carbon transfers among pools) are in mass units of carbon (C) per year, e.g., t
 2565 C/yr. To be consistent with the AFOLU Guidelines, equations are written so that net
 2566 carbon emissions (stock decreases) are negative.³⁸

2567 There are two fundamentally different, but equally valid, approaches to estimating
 2568 carbon stock changes: 1) the stock-based or stock-difference approach and 2) the
 2569 process-based or gain-loss approach. These approaches can be used to estimate stock
 2570 changes in any carbon pool, although as is explained below, their applicability to soil
 2571 carbon stocks is limited. The stock-based approach estimates the difference in carbon
 2572 stocks in a particular pool at two points in time (Equation 2.4.1). This method can be
 2573 used when carbon stocks in relevant pools have been measured and estimated over
 2574 time, such as in national forest inventories. The process-based or gain-loss approach
 2575 estimates the net balance of additions to and removals from a carbon pool (Equation 5-
 2576 2). In the REDD context, gains only result from carbon transfer from another pool (e.g.,
 2577 transfer from a biomass pool to a dead organic matter pool due to disturbance), and
 2578 losses result from carbon transfer to another pool and emissions due to harvesting,
 2579 decomposition or burning. This type of method is used when annual data such as
 2580 biomass growth rates and wood harvests are available. In reality, a mix of the stock-
 2581 difference and gain-loss approaches can be used as discussed further in this chapter.

2582

³⁸ To be consistent with the national greenhouse gas inventory reporting tables established by the IPCC, in which emissions are reported as positive values, emissions would need to be multiplied by negative one (-1).

2583
2584
2585

Equation 2.4.1

2587 Annual Carbon Stock Change in a Given Pool as an Annual Average Difference in Stocks
2588 (Stock-Difference Method)

$$\Delta C = \frac{(C_{t_2} - C_{t_1})}{(t_2 - t_1)}$$

2589
2590

2591 Where:

2592 ΔC = annual carbon stock change in pool (t C/yr)

2593 C_{t_1} = carbon stock in pool in at time t_1 (t C)

2594 C_{t_2} = carbon stock in pool in at time t_2 (t C)

2595 Note: the carbon stock values for some pools may be in t C/ ha, in which case the
2596 difference in carbon stocks will need to be multiplied by an area.

2597

Equation 2.4.2

2599 Annual Carbon Stock Change in a Given Pool As a Function of Annual Gains and Losses
2600 (Gain-Loss Method)

$$\Delta C = \Delta C_G - \Delta C_L$$

2601

2602 Where:

2603 ΔC = annual carbon stock change in pool (t C/yr)

2604 ΔC_G = annual gain in carbon (t C/yr)

2605 ΔC_L = annual loss of carbon (t C/yr)

2606 The stock-difference method is suitable for estimating emissions caused by both
2607 deforestation and forest degradation, and can apply to all carbon pools.³⁹ The carbon
2608 stock for any pool at time t_1 will represent the carbon stock of that pool in the forest of a
2609 particular stratum (see Sections 2.2 and 2.3), and the carbon stock of that pool at time
2610 t_2 will either be zero (the Tier 1 default value for biomass and dead organic matter
2611 immediately after deforestation) or the value for the pool under the new land use (see
2612 section 2.4.5.2) or the value for the pool under the resultant degraded forest. If the
2613 carbon stock values are in units of t C/ha, the change in carbon stocks, ΔC , is then
2614 multiplied by the area deforested or degraded for that particular stratum, and then
2615 divided by the time interval to give an annual estimate.

2616 Estimating the change in carbon stock using the gain-loss method (Equation 2.4.2) is not
2617 likely to be useful for deforestation estimating with a Tier 1 or Tier 2 method, but could
2618 be used for Tier 3 approach for biomass and dead organic matter involving detailed

³⁹Although in theory the stock-difference approach could be used to estimate stock changes in both mineral soils and organic soils, this approach is unlikely to be used in practice due to the expense of measuring soil carbon stocks. The IPCC has adopted different methodologies for soil carbon, which are described below.

2619 forest inventories and/or simulation models. However, the gain-loss method can be used
 2620 for forest degradation to account for the biomass and dead organic matter pools with a
 2621 Tier 2 or Tier 3 approach. Biomass gains would be accounted for with rates of growth,
 2622 and biomass losses would be accounted for with data on timber harvests, fuelwood
 2623 removals, and transfers to the dead organic matter pool due to disturbance. Dead
 2624 organic matter gains would be accounted for with transfers from the live biomass pools
 2625 and losses would be accounted for with rates of dead biomass decomposition.

2626 **2.4.5 Estimation of Emissions from Deforestation**

2627 **2.4.5.1 Disturbance Matrix Documentation**

2628 Land-use conversion, particularly from forests to non-forests, can involve significant
 2629 transfers of carbon among pools. The immediate impacts of land conversion on the
 2630 carbon stocks for each forest stratum can be summarized in a matrix, which describes
 2631 the retention, transfers, and releases of carbon in and from the pools in the original
 2632 land-use due to conversion (Table 2.4.2). The level of detail on these transfers will
 2633 depend on the decision of which carbon pools to include, which in turn will depend on the
 2634 key category analysis (see Table 2.2.2 in Section 2.2). The disturbance matrix defines
 2635 for each pool the proportion of carbon that remains in the pool and the proportions that
 2636 are transferred to other pools. Use of such a matrix in carbon estimating will ensure
 2637 consistency of estimating among carbon pools, as well as help to achieve higher
 2638 accuracy in carbon emissions estimation. Even if all the data in the matrix are not used,
 2639 the matrix can assist in estimation of uncertainties.

2640 **Table 2.4.2: Example of a disturbance matrix for the impacts of deforestation**
 2641 **on carbon pools** (Table 5.7 in the AFOLU Guidelines). Impossible transfers are blacked
 2642 out. In each blank cell, the proportion of each pool on the left side of the matrix that is
 2643 transferred to the pool at the top of each column is entered. Values in each row must
 2644 sum to 1.

To From	Above-ground biomass	Below-ground biomass	Dead wood	Litter	Soil organic matter	Harvested wood products	Atmosphere	Sum of row (must equal 1)
Aboveground biomass								
Belowground biomass								
Dead wood								
Litter								
Soil organic matter								

2645 **2.4.5.2 Changes in Carbon Stocks of Biomass**

2646 The IPCC methods for estimating the annual carbon stock change on land converted to a
 2647 new land-use category include two components:

- 2648 One accounts for the initial change in carbon stocks due to the land conversion,
 2649 e.g., the change in biomass stocks due to forest clearing and conversion to say
 2650 cropland.
- 2651 The other component accounts, in the REDD context, only for the gradual carbon
 2652 loss during a transition period to a new steady-state system.

2653 For the biomass pools, conversion to annual cropland and settlements generally contain
 2654 lower biomass and steady-state is usually reached in a shorter period (e.g., the default
 2655 assumption for annual cropland is 1 year). The time period needed to reach steady state
 2656 in perennial cropland (e.g., orchards) or even grasslands, however, is typically more

2657 than one year. The inclusion of this second component will likely become more important
2658 for future monitoring of the performance of REDD as countries consider moving into a
2659 Tier 3 approach and implement an annual or bi-annual monitoring system.

2660 The initial change in biomass (live or dead) stocks due to land-use conversion is
2661 estimated using a stock-difference approach in which the difference in stocks before and
2662 after conversion is calculated for each stratum of land converted. Equation 2.4.3 (below)
2663 is the equation presented in the AFOLU Guidelines for biomass.

2664 **Equation 2.4.3**

2665 Initial Change in Biomass Carbon Stocks on Land Converted to New Land-Use Category
2666 (Stock-Difference Type Method)

$$\Delta C_{CONV} = \sum [(B_{AFTERi} - B_{BEFOREi}) \cdot \Delta A_i] \cdot CF$$

2667

2668 Where:

2669 ΔC_{CONV} = initial change in biomass carbon stocks on land converted to another land-use
2670 category (t C yr⁻¹)

2671 B_{AFTERi} = biomass stocks on land type *i* immediately after conversion (t dry matter/ha)

2672 $B_{BEFOREi}$ = biomass stocks on land type *i* before conversion (t dry matter/ha)

2673 ΔA_i = area of land type *i* converted (ha)

2674 CF = carbon fraction (t C /t dm)

2675 *i* = stratum of land

2676

2677 The Tier 1 default assumption for biomass and dead organic matter stocks immediately
2678 after conversion of forests to non-forests is that they are zero, whereas the Tier 2
2679 method allows for the biomass and dead organic matter stocks after conversion to have
2680 non-zero values. Disturbance matrices (e.g., Table 2.4.2) can be used to summarize the
2681 fate of biomass and dead organic matter stocks, and to ensure consistency among pools.

2682 The biomass stocks immediately after conversion will depend on the amount of live
2683 biomass removed during conversion. During conversion, aboveground biomass may be
2684 removed as timber or fuelwood, burned and the carbon emitted to the atmosphere or
2685 transferred to the dead wood pool, and/or cut and left on the ground as deadwood; and
2686 belowground biomass may be transferred to the soil organic matter pool (See Ch
2687 2.3.1.1.3). Estimates of default values for the biomass stocks on croplands and
2688 grasslands are given in the AFOLU Guidelines in Table 5.9 (croplands) and Table 6.4
2689 (grasslands). The dead organic matter (DOM) stocks immediately after conversion will
2690 depend on the amount of live biomass killed and transferred to the DOM pools, and the
2691 amount of DOM carbon released to the atmosphere due to burning and decomposition.
2692 In general, croplands (except agroforestry systems) and settlements will have little or no
2693 dead wood and litter so the Tier 1 'after conversion' assumption for these pools may be
2694 reasonable for these land uses.

2695 A two-component approach for biomass and DOM may not be necessary in REDD
2696 estimating. If land-use conversions are permanent, and all that one is interested in is the
2697 total change in carbon stocks, then all that is needed is the carbon stock prior to
2698 conversion, and the carbon stocks after conversion once steady state is reached. These
2699 data would be used in a stock difference method (Equation 2.4.1), with the time interval
2700 the period between land-use conversion and steady-state under the new land use.

2701 **2.4.5.3 Changes in Soil Carbon Stocks**

2702 The IPCC Tier 2 method for mineral soil organic carbon is basically a combination of a
2703 stock-difference method and a gain-loss method (Equation 2.4.4). (The first part of

2704 Equation 2.4.4 [for $\Delta C_{\text{Mineral}}$] is essentially a stock-difference equation, while the second
 2705 part [for SOC] is essentially a gain-loss method with the gains and losses derived from
 2706 the product of reference carbon stocks and stock change factors). The reference carbon
 2707 stock is the soil carbon stock that would have been present under native vegetation on
 2708 that stratum of land, given its climate and soil type.

2709 **Equation 2.4.4**

2710 Annual Change in Organic Carbon Stocks in Mineral Soils

$$\Delta C_{\text{Mineral}} = \frac{(SOC_0 - SOC_{(0-T)})}{D}$$

2711

$$SOC = \sum_{C,S,i} (SOC_{REF_{C,S,i}} \cdot F_{LU_{C,S,i}} \cdot F_{MG_{C,S,i}} \cdot F_{I_{C,S,i}} \cdot \Delta A_{C,S,i})$$

2712

2713 Where:

2714 $\Delta C_{\text{Mineral}}$ = annual change in organic carbon stocks in mineral soils (t C yr⁻¹)

2715 SOC_0 = soil organic carbon stock in the last year of the inventory time period (t
 2716 C)

2717 $SOC_{(0-T)}$ = soil organic carbon stock at the beginning of the inventory time period (t
 2718 C)

2719 T = number of years over a single inventory time period (yr)

2720 D = Time dependence of stock change factors which is the default time period for
 2721 transition between equilibrium SOC values (yr). 20 years is commonly used, but depends
 2722 on assumptions made in computing the factors F_{LU} , F_{MG} , and F_I . If T exceeds D, use the
 2723 value for T to obtain an annual rate of change over the inventory time period (0-T
 2724 years).

2725 c represents the climate zones, s the soil types, and i the set of management
 2726 systems that are present in a country

2727 SOC_{REF} = the reference carbon stock (t C ha⁻¹)

2728 F_{LU} = stock change factor for land-use systems or sub-system for a particular land
 2729 use (dimensionless)

2730 F_{MG} = stock change factor for management regime (dimensionless)

2731 F_I = stock change factor for input of organic matter (dimensionless)

2732 A = land area of the stratum being estimated (ha)

2733

2734 The land areas in each stratum being estimated should have common biophysical
 2735 conditions (i.e., climate and soil type) and management history over the inventory time
 2736 period. Also disturbed forest soils can take many years to reach a new steady state (the
 2737 IPCC default for conversion to cropland is 20 years).

2738 Countries may not have sufficient country-specific data to fully implement a Tier 2
 2739 approach for mineral soils, in which case a mix of country-specific and default data may
 2740 be used. Default data for reference soil organic carbon stocks can be found in Table 2.3
 2741 of the AFOLU Guidelines (see also Ch 4.4.3). Default stock change factors can be found
 2742 in the land-use category chapters of the AFOLU Guidelines (Chapter 4, 5, 6, 7, 8, and 9).

2743 The IPCC Tier 2 method for organic soil carbon is an emission factor method that
 2744 employs annual emission factor that vary by climate type and possibly by management
 2745 system (Equation 2.4.5). However, empirical data from many studies on peat swamp
 2746 soils in Indonesia could be used in such cases—see Box 2.3.1 (Section 2.3).

2747 **Equation 2.4.5**

2748 Annual Carbon Loss from Drained Organic Soils

$$L_{Organic} = \sum_C (A \cdot EF)_C$$

2749

2750 Where:

2751 $L_{Organic}$ = annual carbon loss from drained organic soils (t C yr⁻¹)

2752 A_c = land area of drained organic soils in climate type c (ha)

2753 EF_c = emission factor for climate type c (t C yr⁻¹)

2754 Note that land areas and emission factors can also be disaggregated by management
2755 system, if there are emissions data to support this.

2756

2757 This methodology can be disaggregated further into emissions by management systems
2758 in addition to climate type if appropriate emission factors are available. Default (Tier 1)
2759 emission factors for drained forest, cropland, and grassland soils are found in Tables 4.6,
2760 5.6, and 6.3 of the AFOLU Guidelines.

2761 **2.4.6 Estimation of Emissions from Forest Degradation**

2762 **2.4.6.1 Changes in Carbon Stocks**

2763 For degradation, the main changes in carbon stocks occur in the vegetation (see Table
2764 2.2.2 in Section 2.2). As is discussed in Section 2.3, estimation of soil carbon emissions
2765 is only recommended for intensive practices that involve significant soil disturbance.
2766 Selective logging for timber or fuelwood, whether legal or illegal, in forests on mineral
2767 soil does not typically disturb soils significantly. However, selective logging of forests
2768 growing on organic soils, particularly peat swamps, could result in large emissions caused
2769 by practices such as draining to remove the logs from the forest, and then often followed
2770 by fires (see Box 2.3.1 in Section 2.3). However, in this section guidance is provided
2771 only for the emissions from biomass.

2772 The AFOLU Guidelines recommend either a stock-difference method (Equation 2.4.1) or
2773 a gain-loss method (Equation 2.4.2) for estimating the annual carbon stock change in
2774 "Forests Remaining Forests". In general, both methods are applicable for all tiers. With a
2775 gain-loss approach for estimating emissions, biomass gains would be accounted for with
2776 rates of growth in trees after logging, and biomass losses would be accounted for with
2777 data on timber harvests, fuelwood removals, and transfers of live to the dead organic
2778 matter pool due to disturbance (also see Box 2.2.9 in Section 2.2 for more guidance on
2779 improvements for this approach). With a stock-difference approach, carbon stocks in
2780 each pool would be estimated both before and after degradation (e.g. a timber harvest),
2781 and the difference in carbon stocks in each pool calculated.

2782 The decision regarding whether a stock-difference method or a gain-loss method is used
2783 will depend largely on the availability of existing data and resources to collect additional
2784 data. Estimating the carbon impacts of logging may lend itself more readily to the gain-
2785 loss approach, while estimating the carbon impacts of fire may lend itself more readily to
2786 the stock-difference approach. For example, in the AFOLU Guidelines, details are given
2787 for using the gain-loss method for logging. This approach could be used for all forms of
2788 biomass extraction (timber and fuelwood, legally and illegally extracted) and experience
2789 has shown that if applied correctly can produce more accurate and precise emission
2790 estimates cost effectively (see Box 2.2.9 in Section 2.2).

2791 For Forests Remaining Forests, the Tier 1 assumption is that net carbon stock changes in
2792 DOM are zero, whereas in reality dead wood can decompose relatively slowly, even in
2793 tropical humid climates. Both logging and fires can significantly influence stocks in the
2794 dead wood and litter pools, so countries that are experiencing significant changes in their

2795 forests due to degradation are encouraged to develop domestic data to estimate the
2796 impact of these changes on dead organic matter. It is recommended that the impacts of
2797 degradation on each carbon pool for each forest stratum be summarized in a matrix as
2798 shown in Table 2.4.2 above.

2799

2800

2801 **2.5 METHODS FOR ESTIMATING GHG'S EMISSIONS FROM** 2802 **BIOMASS BURNING**

2803 Luigi Boschetti, University of Maryland, USA

2804 Chris Justice, University of Maryland, USA

2805 David Roy, South Dakota State University, USA

2806 Ivan Csiszar, NOAA, USA

2807 Emilio Chiuvienco, University of Alcala, Spain

2808 Allan Spessa, University of Reading, UK

2809 **2.5.1 Scope of chapter**

2810

2811 Chapter 2.5 is focused on fires in forest environments and how to calculate greenhouse
2812 gas emissions due to vegetation fires, using available satellite-based fire monitoring
2813 products, biomass estimates and coefficients.

2814

2815 Section 2.5.2 introduces emissions due to fire in forest environments and approaches to
2816 estimates emissions from fires.

2817 Section 2.5.3 focuses on the IPCC guidelines for estimating fire-related emission.

2818 Section 2.5.4 focuses on Systems for observing and mapping fire.

2819 Section 2.5.5 describes the potential use of existing fire and burned area products.

2820

2821 **2.5.2 Introduction**

2822 **2.5.2.1 REDD and emissions due to fire in forest environments**

2823 Fire is a complex biophysical process with multiple direct and indirect effects on the
2824 atmosphere, the biosphere and the hydrosphere. Moreover, it is now widely recognized
2825 that, in some fire prone environments, fire disturbance is essential to maintain the
2826 ecosystem in a state of equilibrium.

2827 Reducing the emissions from deforestation and degradation (REDD) from fire, requires
2828 an understanding of the process of fire in forest systems (either as a disturbance, a
2829 forest management tool, or as a process associated with land cover conversion) and how
2830 fire emissions are calculated. The specific details of how REDD will be implemented with
2831 respect to fire are still in development.

2832 This chapter is therefore focused on fires in forest environments and how to calculate
2833 greenhouse gas emissions due to vegetation fires, using available satellite-based fire
2834 monitoring products, biomass estimates and coefficients.

2835 The effects of fire in forest environments are widely variable: it is possible to refer to fire
2836 severity as a term to indicate the magnitude of the effects of the fire on the ecosystem,
2837 which in turn is strongly related to the post-fire status of the ecosystem. As a broad
2838 categorization, low severity ground fires affect mainly the understory vegetation, rather
2839 than the trees, while high severity crown fires affect directly the trees. The latter are
2840 sometimes referred to as stand replacement fires. Consequently at the broad scale,

2841 ground fires do not alter the equilibrium of the ecosystem (i.e. do not result in a
2842 conversion from forest to non forest cover), while most crown fires lead to a forest-non
2843 forest temporary transition (i.e. disturbance) or in some cases to a permanent landcover
2844 change

2845 The issue of the definition of forest (described in detail in chapter 2.2) is a particularly
2846 sensitive one when the fire monitoring from satellite data is concerned. Within the 10 to
2847 30 percent tree crown cover range indicated by the Marrakech Accords, most of woody
2848 savannah ecosystems might or might not be considered as forest. These are the
2849 ecosystems where most of the biomass burning occurs (Roy et al., 2008, van der Werf,
2850 2003) and where fire contributes to maintaining the present landcover: for example high
2851 fire frequency (fire return interval of a few years) inhibits young tree growth and blocks
2852 the transition from open to closed woodland ecosystem.

2853 Different fire management practices in different ecosystems can determine the amount
2854 of trace-gas and particulate emissions and changes the forest carbon stocks. In closed
2855 forest, controlled ground fires reduce the amount of biomass in the understory and
2856 reduce the occurrence of high severity, stand replacement fires. Conversely, in open
2857 woodland systems reducing the occurrence of fire allows tree growth with the
2858 subsequent effect of carbon sequestration. Furthermore, emission coefficients do have a
2859 seasonal variability: even assuming that fires affect the same areal extent, shifting the
2860 timing of the burning (early season versus late season) can have a significant effect on
2861 the total emissions. Early season burning when the vegetation is moist is often
2862 recommended as a good fire management practice in savanna woodlands as the fires are
2863 less damaging to the ecosystem.

2864 The purpose of this chapter is to present and explain the IPCC guidelines, list the
2865 available sources of geographically distributed data to be used for the emissions
2866 estimation, illustrate some of the main issues and uncertainties associated with the
2867 various steps of the methodology. Drawing from the experience of GOFC-GOLD Fire
2868 Implementation Team and Regional Fire Networks, the chapter emphasizes the possible
2869 use of satellite derived products and information.

2870 **2.5.2.2 Direct and indirect approach to emission estimates**

2871 Estimates of atmospheric emissions due to biomass burning have conventionally been
2872 derived adopting 'bottom up' inventory based methods (Seiler and Crutzen, 1980) as:

$$2873 \quad L = A \times Mb \times Cf \times Gef \quad \text{[Equation 2.5.1]}$$

2874 where the quantity of emitted gas or particulate L [g] is the product of the area affected
2875 by fire A [m²], the fuel loading per unit area Mb [g m⁻²], the combustion factor Cf , i.e.
2876 the proportion of biomass consumed as a result of fire [g g⁻¹], and the emission factor or
2877 emission ratio Gef , i.e. the amount of gas released for each gaseous specie per unit of
2878 biomass load consumed by the fire [g g⁻¹].

2879 Rather than attempting to measure directly the emissions L , this method requires to
2880 estimate the pre-fire biomass ($A \times Mb$), then estimate what portion of it burned (Cf) and
2881 finally convert the total biomass burned ($A \times Mb \times Cf$) into emissions by means of the
2882 coefficient Gef . For this reason, it is defined as an indirect method. The main issue with
2883 the indirect method is that, being L the result of the multiplication of four independent
2884 terms, their uncertainties will propagate into the uncertainty of the estimate L . As a
2885 consequence, a precise estimate of L requires a precise estimate of all the terms of
2886 equation 2.5.1.

2887 The area burned (A) was considered as the parameter with the greatest uncertainty
2888 (Seiler and Crutzen, 1980) but in the last decade significant improvements in the
2889 systematic mapping of area burned from satellite data have been made (Roy et al.
2890 2008). Fuel load (Mb) remains an uncertain parameter and has been variously estimated
2891 from sample field data, satellite data and models (including those partially driven by
2892 satellite data) calculating Net Primary Production to provide biomass increments and
2893 partitioning between fuel classes (Van der Werf et al., 2003). Emission factors (Gef) are

2894 largely well-determined from laboratory measurements, although aerosol emission
2895 factors and the temporal dynamics of emission factors as a function of fuel moisture
2896 content are less certain. The burning efficiency (Cf) is a function of fire
2897 condition/behavior, the relative proportions of woody, grass, and leaf litter fuels, the fuel
2898 moisture content and the uniformity of the fuel bed. Dependencies on cover type can
2899 potentially be specified by the use of satellite-derived land cover classifications or related
2900 products such as the percentage tree cover product of Hansen et al. (2002)⁴⁰, used by
2901 Korontzi et al. (2004) to distinguish grasslands and woodlands in Southern Africa.
2902 Korontzi et al. (2004) modeled a term related to Cf (combustion completeness, CC) as a
2903 weighted proportion of fuel types and emission factor database values. Roy and
2904 Landmann (2005)⁴¹ stated that there is no direct method to estimate CC from remote
2905 sensing data, although they demonstrated a near linear relationship between the product
2906 of CC and the proportion of a satellite pixel affected by fire and the relative change in
2907 short wave infrared reflectance.

2908

2909 Rather than estimate $A \times Mb \times Cf$ independently, a recently proposed alternative is to
2910 directly measure the power emitted by actively burning fires and from this estimate the
2911 total biomass consumed. The radiative component of the energy released by burning
2912 vegetation can be remotely sensed at mid infrared and thermal infrared wavelengths
2913 (Ichoku and Kaufman, 2005⁴², Wooster et al. 2005, Smith and Wooster 2005⁴³). This
2914 instantaneous measure, the Fire Radiative Power (FRP) expressed in Watts [W], has
2915 been shown to be related to the rate of consumption of biomass [g/s]. Importantly this
2916 method provides accurate (i.e. $\pm 15\%$) estimates of the rate of fuel consumed (Wooster
2917 et al 2005) and the integral of the FRP over the fire duration, the Fire Radiative Energy
2918 (FRE) expressed in Joules [J], has been shown to be linearly related to the total biomass
2919 consumed by fire [g] (Smith and Wooster, 2005, Wooster et al., 2005, Freeborn 2008⁴⁴).
2920 However, the accuracy of the integration of FRP over time to derive FRE depends on the
2921 spatial and temporal sampling of the emitted power. Ideally, the integration requires
2922 high spatial resolution and continuous observation over time, while the currently
2923 available systems provide low spatial resolution and high temporal resolution
2924 (geostationary satellites) or moderate spatial resolution and low temporal resolution
2925 (polar orbiting systems). For this reason, direct methods have yet to transition from the
2926 research domain to operational application, and at this stage they are not a viable
2927 alternative to indirect methods for GHG inventories in the context of REDD.

2928

⁴⁰ Hansen, M.C., DeFries R.S., Townsend, J.G.R, Carroll, M., Dimiceli, C. and Sohlberg, R.A, Percent Tree Cover at a Spatial Resolution of 500 Meters: First Results of the MODIS Vegetation Continuous Field Algorithm, *Earth Interactions*, 7:1-15.

⁴¹ Roy, D.P. and Landmann, T., (2005), Characterizing the surface heterogeneity of fire effects using multi-temporal reflective wavelength data, *International Journal of Remote Sensing*, 26:4197-4218

⁴² Ichoku, C and Kaufman, Y., (2005), A method to derive smoke emission rates from MODIS Fire Radiative Energy Measurements, *IEEE Transaction on Geosciences and Remote Sensing*, 43(11), 2636-2649 DOI 10.1109/TGRS.2005.857328

⁴³ Smith A.M.S., and Wooster, M.J., (2005), Remote classification of head and backfire types from MODIS fire radiative power observations, *International Journal of Wildland Fire*, 14, 249-254.

⁴⁴ Freeborn, P.H., Wooster, M.J., Hao, W.M., Ryan, C.A., Nordgren, B.L. Baker, S.P. and Ichoku, C.(2008) Relationships between energy release, fuel mass loss, and trace gas and aerosol emissions during laboratory biomass fires, *J. Geophys. Res.*, 113, D01102, doi:10.1029/2007JD008489

2929 **2.5.3 IPCC guidelines for estimating fire-related emission**

2930

2931 The IPCC guidelines include the use of an indirect method for emissions estimates, and
2932 include a three tiered approach to CO₂ and non-CO₂ emissions from fire, Tier 1 using
2933 mostly default values for equation 2.5.1, and Tiers 2 and 3 including increasingly more
2934 site-specific formulations for fuel loads and coefficients.

2935

2936 Using the units adopted in the IPCC guidelines, equation 2.5.1 is written as:

2937

$$2938 \quad L_{\text{fire}} = A \times M_b \times C_f \times G_{\text{ef}} \times 10^{-3} \quad \text{[Equation 2.5.2]}$$

2939

2940 where L is expressed in tonnes of each gas

2941 A in hectares

2942 M_b in tonnes/hectare

2943 C_f is adimensional

2944 G_{ef} in grams/kilogram

2945

2946 The Area burned A [ha] should be characterised as a function of forest types of different
2947 climate or ecological zones and, within each forest type, characterised in terms of fire
2948 characteristics (crown fire, surface fire, land clearing fire, slash and burn...).

2949

2950 In Tier 1, emissions of CO₂ from dead organic matter are assumed to be zero in forests
2951 that are burnt, but not fully destroyed by fire. If the fire is of sufficient intensity to
2952 destroy a portion of the forest stand, under Tier 1 methodology, the carbon contained in
2953 the killed biomass is assumed to be immediately released to the atmosphere. This Tier 1
2954 simplification may result in an overestimation of actual emissions in the year of the fire,
2955 if the amount of biomass carbon destroyed by the fire is greater than the amount of
2956 dead wood and litter carbon consumed by the fire. Non-CO₂ greenhouse gas emissions
2957 are estimated for all fire situations. Under Tier 1, non-CO₂ emissions are best estimated
2958 using the actual fuel consumption provided in AFOLU Table 2.4, and appropriate
2959 emission factors (Table 2.5) (i.e., not including newly killed biomass as a component of
2960 the fuel consumed).

2961

2962 For Forest Land converted to another land uses, organic matter burnt is derived from
2963 both newly felled vegetation and existing dead organic matter, and CO₂ emissions
2964 should be reported. In this situation, estimates of total fuel consumed (AFOLU Table 2.4)
2965 can be used to estimate emissions of CO₂ and non- greenhouse gases using equation
2966 2.5.2.

2967

2968 In the case of Tier 1 calculations, AFOLU Tables 2.4 through 2.6 provide the all the
2969 default values of M_b [t/ha], C_f [t/t] and G_{ef} [g/kg] to be used for each forest type
2970 according to the fire characteristics.

2971 Tier 2 methods employ the same general approach as Tier 1 but make use of more
2972 refined country-derived emission factors and/or more refined estimates of fuel densities
2973 and combustion factors than those provided in the default tables. Tier 3 methods are
2974 more comprehensive and include considerations of the dynamics of fuels (biomass and
2975 dead organic matter).

2976

2977 **2.5.4 Mapping fire from space**

2978 **2.5.4.1 Systems for observing and mapping fire**

2979 Fire monitoring from satellites falls into three primary categories, detection of active
2980 fires, mapping of post fire burned areas (fire scars) and fire characterization (e.g. fire
2981 severity, energy released). For the purposes of emission estimation we are primarily
2982 interested in the latter two categories. Nonetheless, the detection of active fires may be
2983 useful in terms of assessing fire history and the effectiveness of fire exclusion. Satellite
2984 data can contribute to early warning systems for fire (providing information on
2985 vegetation type and condition) which can then be used to better manage fire but this
2986 aspect is not addressed in this chapter.

2987 Satellite systems for Earth Observation are currently providing data with a wide range of
2988 spatial resolutions. Using the common terminology, the resolution can be classified as:

- 2989 • Fine or Hyperspatial (1-10 meter pixel size). Examples: Ikonos, Quick Bird
- 2990 • Moderate or High Resolution⁴⁵: pixel size from 10 to 100 meters. Example:
2991 SPOT, Landsat, CBERS
- 2992 • Coarse resolution: pixel size over 100 meters. Examples: MODIS, MERIS,
2993 SPOT-VGT, AVHRR.

2994 While in principle only hyperspatial and high resolution data can provide the sub-hectare
2995 mapping required for REDD, the tradeoffs between spatial, radiometric, spectral and
2996 temporal resolution of satellite systems need to be taken into account. Higher resolution
2997 images have a low temporal resolution (15-20 days in the case of Landsat-class sensors)
2998 and non-systematic acquisition (especially the hyperspatial sensors). Combined with
2999 missing data from these optical systems due to cloud cover, the data availability is, in
3000 most if not all circumstance, inadequate to monitor an inherently multi-temporal
3001 phenomenon like fire. The recent availability of IRS AWiFS data with 3-5 acquisitions
3002 each month at c. 60m resolution, raises the possibility of increased temporal resolution
3003 at moderate/high resolution.

3004 Moreover, for technological and commercial reasons hyperspatial sensors acquire data
3005 almost exclusively in the visible and near infrared wavelengths, and do not have the
3006 spectral bands required for adequate fire mapping and characterization.

3007

3008 Moreover, for technological and commercial reasons hyperspatial sensors acquire data
3009 almost exclusively in the visible and near infrared wavelengths, and do not have the
3010 spectral bands required for mapping active fires and burned areas (e.g. thermal and
3011 shortwave infrared) and for their characterization (i.e. middle- infrared) .

3012 Conversely, coarse resolution systems do not have the spatial resolution require for sub-
3013 hectare mapping (as an example, a single nadir pixel from MODIS covers 6.25 to 100 ha
3014 depending on the band), but their daily temporal resolution and multispectral capabilities
3015 have allowed in recent years the development of several fire-related global, multiannual
3016 products.

3017 While these products might not immediately satisfy the requirements for compiling
3018 detailed emission inventories, they are a valuable source of information particularly for

⁴⁵ Traditionally Landsat and SPOT data have been referred to as 'high' spatial resolution. The use of the term moderate resolution to include Landsat class observation is a relatively new development but is not common in the literature.

3019 large areas and can be integrated with higher resolution data to produce burned area
 3020 maps at the desired resolution. Section 2.5.3.4 describes possible strategies for the
 3021 combined use of moderate resolution products and high resolution imagery.

3022 **2.5.4.2 Available Fire Related Products**

3023

3024 **Table 2.5.1: List of operational and systematic continental and global active fire**
 3025 **and burned area monitoring systems, derived from satellite data.**

3026

Satellite-based fire monitoring	Information and data access
Global burnt areas 2000-2007: L3JRC (EC Joint Research Center)	http://www-tem.jrc.it/Disturbance_by_fire/products/burnt_areas/GlobalBurntAreas2000-2007.htm
MODIS active fires and burned areas (University of Maryland /NASA)	http://modis-fire.umd.edu
FIRMS: Fire Information for Resource Management System (University of Maryland /NASA/UN FAO)	http://maps.geog.umd.edu/firms
Globcarbon products (ESA)	http://www.fao.org/gtos/tcopjs4.html
World Fire Atlas (ESA)	http://dup.esrin.esa.int/ionia/wfa/index.asp
Global Fire Emissions Database (GFED2) - multi-year burned area and emissions By NASA	http://ess1.ess.uci.edu/%7Ejranders/data/GFED2/
TRMM VIRS fire product (NASA)	http://daac.gsfc.nasa.gov/precipitation/trmmVirFire.shtml
Meteosat Second Generation SEVIRI fire monitoring (EUMETSAT)	http://www.eumetsat.int/Home/Main/Access_to_Data/Meteosat_Meteorological_Products/Product_List/index.htm#FIR
Experimental Wildfire Automated Biomass Burning Algorithm: GOES WF-ABBA (University of Wisconsin-Madison / NOAA)	http://cimss.ssec.wisc.edu/goes/burn/wfabba.html

3027

3028 All the products of table 2.5.1 are derived from coarse resolution systems, either in polar
 3029 or geostationary orbit. Polar-orbiting satellites have the advantage of global coverage
 3030 and typically higher spatial resolution (currently 250 m - 1km). Multi-year global active
 3031 fire data records have been generated from the Advanced Very High Resolution
 3032 Radiometer (AVHRR), the Along-Track Scanning Radiometer (ATSR), and the Moderate
 3033 Resolution Imaging Spectroradiometer (MODIS). The heritage AVHRR and ATSR sensors
 3034 were not designed for active fire monitoring and therefore provide less accurate
 3035 detection. MODIS and the future AVHRR follow-on VIIRS (Visible Infrared Imager
 3036 Radiometer Suite) have dedicated bands for fire monitoring. These sensors, flown on
 3037 sun-synchronous satellite platforms provide only a few daily snapshots of fire activity at
 3038 about the same local time each day, sampling the diurnal cycle of fire activity. The VIRS
 3039 (Visible and Infrared Scanner) on the sun-asynchronous TRMM (Tropical Rainfall

3040 Measuring Mission) satellite covers the entire diurnal cycle but with a longer revisiting
3041 time.

3042

3043 Geostationary satellites allow for active fire monitoring at a higher temporal frequency
3044 (15-30 minutes) on a hemispheric basis, but typically at coarser spatial resolution
3045 (approx 2-4 km). Regional active fire products exist based on data from the
3046 Geostationary Operational Environmental Satellite (GOES) and METEOSAT Second
3047 Generation (MSG) Spinning Enhanced Visible and Infrared Imager (SEVIRI). A major
3048 international effort is being undertaken by GOC-GOLD to develop a global system of
3049 geostationary fire monitoring that will combine data from a number of additional
3050 operational sensors to provide near-global coverage.

3051 Several global burned area products exist for specific years and a number of multi-year
3052 burned area products have been recently released (MODIS, L3JRC, GLOBCARBON) based
3053 on coarse resolution satellite data. The only long term burned area dataset currently
3054 available (GFED2) is partly based on active fire detections. Direct estimating of carbon
3055 emissions from these active fire detections or burned area has improved recently, with
3056 the use of biogeochemical models, but yet fails to capture fine-scale fire processes due
3057 to coarse resolution of the models.

3058 The potential research, policy and management applications of satellite products place a
3059 high priority on providing statements about their accuracy (Morissette et al. 2006), and
3060 this applies to fire related products, if used in the REDD context. Inter-comparison of
3061 products made with different satellite data and/or algorithms provide an indication of
3062 gross differences and possibly insights into the reasons for the differences. However
3063 product comparison with independent reference data is needed to determine accuracy
3064 (Justice et al. 2000)⁴⁶. While all the main active fire and burned area products have been
3065 partially validated with independent data, systematic, global scale, multiannual
3066 validation and systematic reporting have yet to be achieved.

3067

3068 **2.5.4.3 Active Fire versus Burned Area products**

3069 Active fire products provide the location of all fires actively burning at the overpass time.
3070 The short persistence of the signal of active fires means that active fires products are
3071 very sensitive to the daily dynamics of biomass burning, and that in situations where the
3072 fire front moves quickly, there will be an under-sampling of fire dynamics. Based on the
3073 physical characteristics of the sensor, on the characteristics of the fire and on the
3074 algorithm used for the detection, a minimum fire size is required to trigger detection.
3075 This size is orders of magnitude smaller than the pixel size: as an example, for the
3076 MODIS active fire product (Giglio et al, 2003) fires covering around 100m² within the
3077 1km² pixel have a 90% probability of detection in temperate deciduous forest.

3078 Conversely, burned area products generally require that a significant portion of the pixel
3079 (in the order of half of the pixel) is burned to lead to detection. In some cases this
3080 causes a significant underestimation by burned area products, especially in forests,
3081 where fires due to clearings and deforestation are smaller than the pixel size of coarse
3082 resolution systems. In many of these cases, fires resulting in burned areas too small for
3083 detection are large enough to be detected by active fire products. In all cases, users
3084 should not use active fires detections directly in area calculations without proper
3085 calibration, because the area affected by the fire can be significantly smaller than the
3086 pixel size.

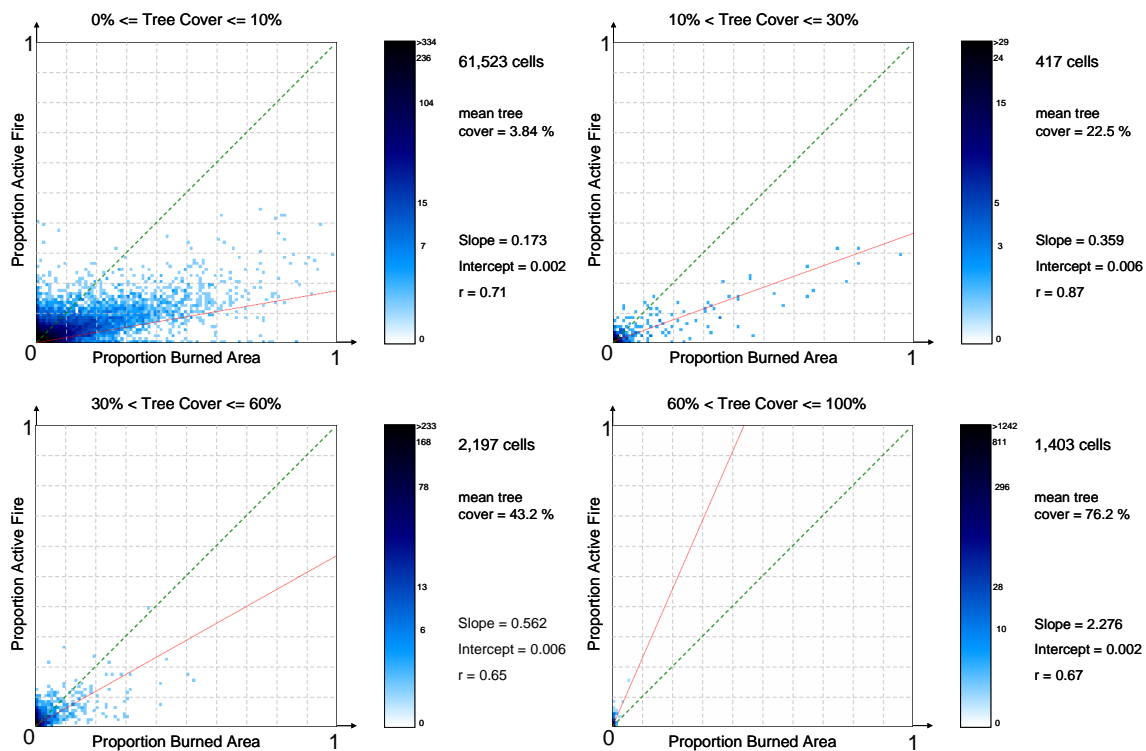
⁴⁶ Justice, C.O., Belward, A., Morissette, J., Lewis, P., Privette, J., Baret, F., (2000), Developments in the 'validation' of satellite sensor products for the study of land surface. *International Journal of Remote Sensing*, 21, 3383-3390.

3087 The systematic comparison of Active Fires and Burned Area products (Roy et al., 2008,
 3088 Tansey et al., 2008⁴⁷) shows that, depending on the type of environment, the ratio
 3089 between the number of active fire detections and burned area detections changes
 3090 significantly, with more burned area detections in grasslands, savannas and open
 3091 woodlands, and more active fire detections than burned area detections in closed forest
 3092 ecosystems.

3093

3094 **Figure 2.5.1:** Scatter plots of the monthly proportions of 40x40km cells labeled as
 3095 burned by the 1km active fire detections plotted against the proportion labeled as
 3096 burned by the 500m burned area product, for four tree cover class ranges, globally,
 3097 period July 2001 to June 2002. Only cells with at least 90% of their area meeting these
 3098 tree cover range criteria and containing some proportion burned in either the active fire
 3099 or the monthly burned area products are plotted. The Theil-Sen regression line is plotted
 3100 in red; the white-blue logarithmic color scale illustrates the frequency of cells having the
 3101 same specific x and y axis proportion values (Source: Roy et al, 2008)

3102



3103

3104

3105 For their physical nature, ground fires generally cannot be detected by burned area
 3106 algorithms. If the crown of the trees is not affected, in closed forest the change in
 3107 reflectance as detected by the satellite is not large enough to be detected. Active fire
 3108 detection algorithms rely instead on the thermal signal due to the energy released by the
 3109 fire and can detect ground fires.

3110 Standard active fire products are generally available within 24 hours of satellite
 3111 overpass. Some satellite-based fire monitoring systems, including those based on the

⁴⁷ Tansey, K.J., Beston, J, Hoscolo, A., Page, S.E. and Paredes Hernandez, C.U., (2008), Relationship between MODIS fire hot spot count and burned area in a degraded tropical forest swamp forest in Central Kalimantan, Indonesia, Journal of Geophysical Research, 113(D23112), doi:10.1029/2008JD010717

3112 processing of direct readout data provide near-real time information. For example, the
3113 Fire Information for Resource Management System (FIRMS), in collaboration with MODIS
3114 Rapid Response uses data transmitted by the MODIS instrument on board NASA's Terra
3115 and Aqua satellites available within two hours of acquisition (Davies et al. 2009). These
3116 data are processed to produce maps, images and text files, including 'fire email alerts'
3117 pertaining to active fire locations to notify protected area, and natural resource
3118 managers of fires in their area of interest.

3119 Burned area products are instead available with days or weeks after the fire event,
3120 because the detection is generally performed using a time series of pre-fire and post-fire
3121 data.

3122 **2.5.5 Using existing products**

3123 Fire is often associated with forest cover change (deforestation, forest degradation)
3124 either through deliberate human clearing or wildfire events. As has been described
3125 above, satellite data can be used to detect forest fires and map the resulting burned
3126 area.

3127 The computation of the total emissions using the indirect approach of Equation 2.5.1
3128 requires burned area maps at a spatial resolution which is not currently provided by any
3129 of the automatic systems of table 2.5.1. Furthermore, the areas burned must be
3130 characterised in terms of fire behaviour (ground fires, crown fires) and in terms of land
3131 use change (fires in forest remaining forest, fires related to deforestation). This
3132 information is also not routinely available as ancillary information of the systematic
3133 global and continental products.

3134 On the other hand, systems of the Landsat class - or higher resolution - do provide the
3135 required spatial resolution, but there are currently no systematic products using those
3136 data, and issues related to data availability (satellite overpass, cloudiness, receiving
3137 stations) make it unrealistic, at the current stage, to envision such automatic issues, set
3138 aside the computational requirement of systematically process high resolution data, even
3139 at country level.

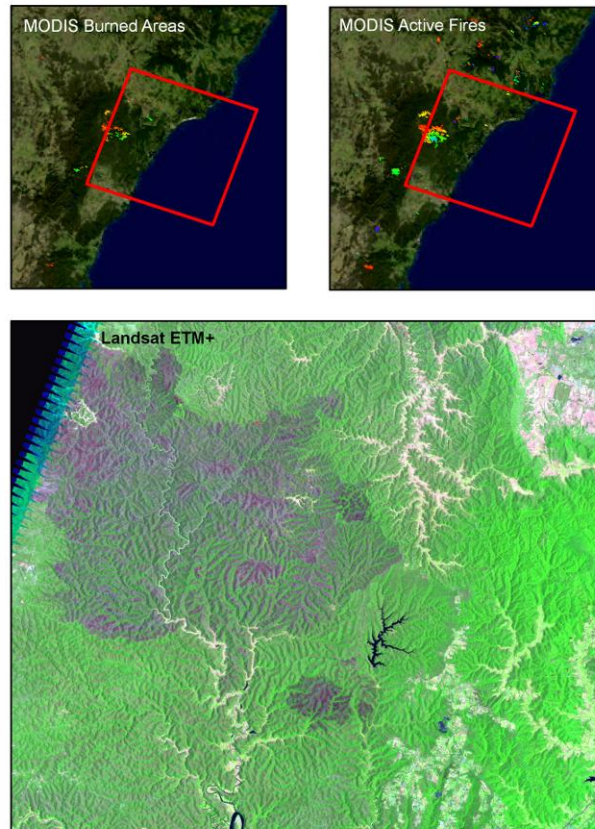
3140 The most promising avenue for producing burned area information with the required
3141 characteristics for GHG emission computation would be instead the integrated use of
3142 high resolution imagery and coarse resolution systematic products. The opening of the
3143 Landsat archive free of charge, and the expanding network of receiving stations of free
3144 data like CBERS make it possible to use extensively high resolution data for refining the
3145 coarse resolution fire information available, also free of charge, as part of the systematic
3146 products.

3147

3148 The coarse resolution products can be used for the systematic monitoring of fire activity
3149 at national scale: when active fires and burned areas are detected in areas of potential
3150 interest for deforestation or for forest degradation, they could be complemented by
3151 acquiring moderate and high resolution imagery covering the spatial extent and the
3152 exact time period of the burning. Through visual interpretation of the moderate and high
3153 resolution data, and using the coarse resolution products as ancillary datasets, it is
3154 possible to produce in a timely and cost effective manner the high resolution burned
3155 area maps required by Equation 2.5.1. (figure 2.5.2)

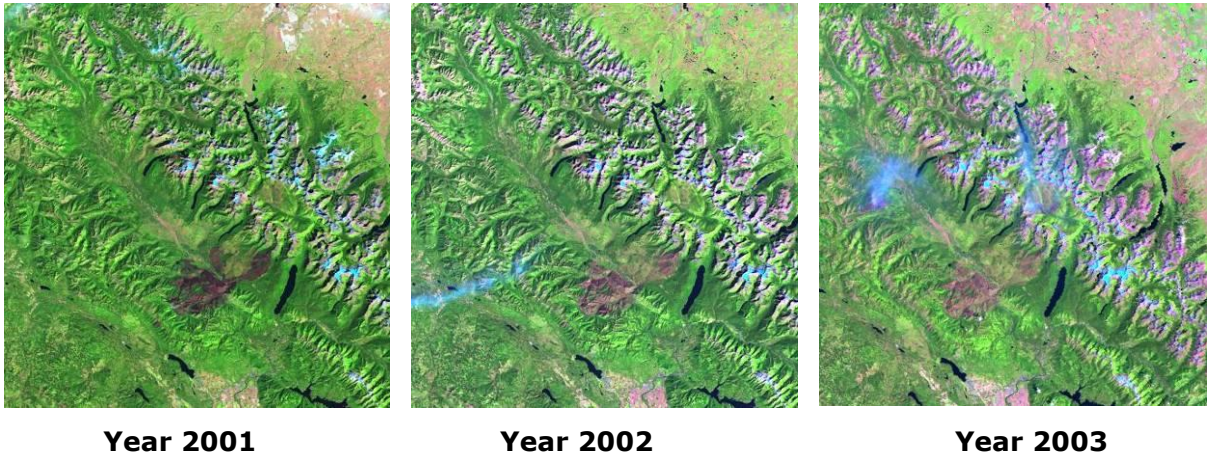
3156

3157 **Figure 2.5.2: Large fire in an open Eucalyptus forest in South East Australia, October 2002.**
3158 The ground fire is only partially detected by the coarse/moderate
3159 resolution MODIS products (top row). On the basis of the information given by such
3160 products it is possible to select the time and location for higher resolution imagery
3161 (Landsat ETM+ data, bottom row) that allows mapping burned area with c. 0.1 ha spatial
3162 resolution.



3163
3164 Furthermore, monitoring with higher resolution imagery over time the location of fire
3165 detections if the fire led to land cover change (forest degradation, stand replacement)
3166 and if land use change occurred after the fire (e.g. conversion to agriculture) (figure
3167 2.5.3).

3168 **Figure 2.5.3: Multitemporal Landsat TM/ETM+ imagery of a forest fire in**
3169 **Western Montana, USA.** The first image (left) is acquired shortly after the fire, and the
3170 other two at one year intervals. The inspection of multitemporal imagery after the fire
3171 allows monitoring whether land cover and land use changes occur after the fire.



3174
3175

3176 **2.5.6 Key references for Section 2.5**

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- 3198

3199

3200 **2.6 UNCERTAINTIES**

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3202 Martin Herold, Friedrich Schiller University Jena, Germany

3203 Giacomo Grassi, Joint Research Centre, Italy

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3205 **2.6.1 Scope of chapter**

3206 Uncertainty is an unavoidable attribute of practically any type of data including area and
3207 carbon stock estimates in the REDD context. Identification of the sources and
3208 quantification of the magnitude of uncertainty will help to better understand the
3209 contribution of each parameter to the overall accuracy and precision of the REDD
3210 estimates, and to prioritize efforts for their further development.

3211 The proper manner of dealing with uncertainty is fundamental in the IPCC and UNFCCC
3212 contexts: The IPCC defines inventories consistent with good practice as those which
3213 contain neither over- nor underestimates so far as can be judged, and in which
3214 uncertainties are reduced as far as practicable.

3215 In the accounting context, information on uncertainty can be used to develop
3216 conservative REDD estimates⁴⁸. This principle has been included in the REDD negotiating
3217 text which emphasizes the need "to deal with uncertainties in estimates aiming to ensure
3218 that reductions in emissions or increases in removals are not over-estimated"⁴⁹.

3219 Building on the IPCC Guidance, this section aims to provide some basic elements for a
3220 correct estimation on uncertainties. After a brief explanation of general concepts
3221 (Section 2.6.2), some key aspects linked to the quantification of uncertainties are
3222 illustrated for both area and carbon stocks (Section 2.6.3). The section concludes with
3223 the methods available for combining uncertainties (Section 2.6.4) and with the standard
3224 reporting and documentation requirements (Section 2.6.5).

3225 **2.6.2 General concepts**

3226 The most important concepts needed for estimation of uncertainties are explained below.

3227

3228 **Bias** is a systematic error, which can occur, e.g. due to flaws in the measurements or
3229 sampling methods or due to the use of an emission factor which is not suitable for the
3230 case to which it is applied. Bias means lack of accuracy.

3231 **Accuracy** is the agreement between the true value and repeated measured observations
3232 or estimations of a quantity. Accuracy means lack of bias.

3233 **Random error** describes the random variation above or below a mean value, and is
3234 inversely proportional to precision. Random error cannot be fully avoided, but can be
3235 reduced by, for example, increasing the sample size.

⁴⁸ See Section 4.4 How to deal with uncertainties: the conservativeness approach

⁴⁹ FCCC/SBSTA/2008/L.12

3236 **Precision** illustrates the level of agreement among repeated measurements of the same
3237 quantity. This is represented by how closely grouped the results from the various
3238 sampling points or plots are. Precision is inversely proportional to random error.

3239 **Uncertainty** means the lack of knowledge of the true value of a variable, including both
3240 bias and random error. Thus uncertainty depends on the state of knowledge of the
3241 analyst, which depends, e.g., on the quality and quantity of data available and on the
3242 knowledge of underlying processes. Uncertainty can be expressed as a percentage
3243 confidence interval relative to the mean value. For example, if the area of forest land
3244 converted to cropland (mean value) is 100 ha, with a 95% confidence interval ranging
3245 from 90 to 110 ha, we can say that the uncertainty in the area estimate is $\pm 10\%$.

3246 **Confidence interval** is a range that encloses the true value of an unknown parameter
3247 with a specified confidence (probability). In the context of estimation of emissions and
3248 removals under the UNFCCC, a 95% confidence interval is normally used. The 95 percent
3249 confidence interval has a 95 percent probability of enclosing the true but unknown value
3250 of the parameter. The 95 percent confidence interval is enclosed by the 2.5th and 97.5th
3251 percentiles of the probability density function.

3252 **Correlation** means dependency between parameters. It can be described with Pearson
3253 correlation coefficient which assumes values between $[-1, +1]$. Correlation coefficient of
3254 $+1$ presents a perfect positive correlation, which can occur for example when the same
3255 emission factor is used for different years. In the case the variables are independent of
3256 each other, the correlation coefficient is 0.

3257 **Trend** describes the change of emissions or removals between two points in time. In the
3258 REDD context, the trend will likely be more important than the absolute values.

3259 **Trend uncertainty** describes the uncertainty in the change of emissions or removals
3260 (i.e. trend). Trend uncertainty is sensitive to the correlation between parameters used to
3261 estimate emissions or removals in the two years. Trend uncertainty is expressed as
3262 percentage points. For example, if the trend is $+5\%$ and the 95% confidence interval of
3263 the trend is $+3$ to $+7\%$, we can say that trend uncertainty is $\pm 2\%$ points.

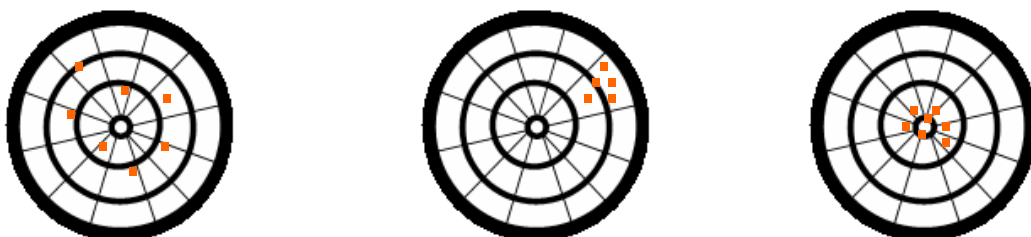
3264

3265 The above mentioned concepts of bias, accuracy, random error and precision can be
3266 illustrated by an analogy with bull's eye on a target. In this analogy, how tightly the
3267 darts are grouped is the precision, how close they are to the center is the accuracy.
3268 Below in Figure 2.6.1 (A), the points are close to the center and are therefore accurate
3269 (lacking bias) but they are widely spaced and therefore are imprecise. In (B), the points
3270 are closely grouped and therefore are precise (lacking random error) and but are far
3271 from the center and so are inaccurate (i.e biased). Finally, in (C), the points are close to
3272 the center and tightly grouped and are both accurate and precise.

3273

3274 **Figure 2.6.1: Illustration of the concepts of accuracy and precision.**

3275 (A) Accurate but not precise (B) Precise but not accurate (C) Accurate and precise



3276

3277

3278 **2.6.3 Quantification of uncertainties**

3279 The first step in an uncertainty analysis is to identify the potential sources of uncertainty.
3280 These can be, for example, measurement errors due to human errors or errors in
3281 calibration; modeling errors due to inability of the model to fully describe the
3282 phenomenon; sampling errors due to too small or unrepresentative sample; or
3283 definitions or classifications which are erroneously used leading to double-counting or
3284 non-counting.

3285

3286 **2.6.3.1 Uncertainties in area estimates**

3287 One way of estimating the activity data (i.e. area of a land category) is simply to report
3288 the area as indicated on the map derived from remote sensing. While this approach is
3289 common, it fails to recognize that maps derived from remote sensing contain
3290 classification errors. There are many factors that contribute to errors in remote sensing
3291 maps, and they are discussed below. A suitable approach is to assess the accuracy of
3292 the map and use the results of the accuracy assessment to adjust the area estimates.
3293 Such an approach accounts for the biases found in the map and allows for improved area
3294 estimates. Most image classification methods have parameters that can be tuned to get
3295 a reasonable amount of pixels in each class. A good tuning reduces the bias, but has a
3296 certain degree of subjectivity. Assessing the margin for subjectivity is a necessary task.

3297

3298 An accuracy assessment using a sample of higher quality data should be an integral part
3299 of any national monitoring and accounting system. If the sample for the higher quality
3300 data is statistically rigorous (e.g.: random, stratified, systematic), a calibration estimator
3301 (or similar) gives better results than the original survey. Chapter 5 of IPCC Good Practice
3302 Guidance 2003 provides some recommendations and emphasizes that they should be
3303 quantified and reduced as far as practicable.

3304

3305 For the case of using remote sensing to derive land change activity data, the accuracy
3306 assessment should lead to a quantitative description of the uncertainty of the area for
3307 land categories and the associated change in area observed. This may entail category
3308 specific thematic accuracy measures, confidence intervals for the area estimates, or an
3309 adjustment of the initial area statistics considering known and quantified biases to
3310 provide the best estimate. Deriving statistically robust and quantitative assessment of
3311 uncertainties is a substantial task and should be an ultimate objective. Any validation
3312 should be approached as a process using "best efforts" and "continuous improvement",
3313 while working towards a complete and statistically robust uncertainty assessment that
3314 may only be achieved in the future.

3315

3316 **2.6.3.1.1 Sources of error**

3317 Different components of the monitoring system affect the quality of the outcomes. They
3318 include:

- 3319 • the quality and suitability of the satellite data (i.e. in terms of spatial, spectral,
3320 and temporal resolution),
- 3321 • the interoperability of different sensors or sensor generations
- 3322 • the radiometric and geometric preprocessing (i.e. correct geolocation),
- 3323 • the cartographic and thematic standards (i.e. land category definitions and MMU)
- 3324 • the interpretation procedure (i.e. classification algorithm or visual interpretation)

- 3325 • the post-processing of the map products (i.e. dealing with no data values,
3326 conversions, integration with different data formats, e.g. vector versus raster),
3327 and
- 3328 • the availability of reference data (e.g. ground truth data) for evaluation and
3329 calibration of the system

3330

3331 Given the experiences from a variety of large-scale land cover monitoring systems,
3332 many of these error sources can be properly addressed during the monitoring process
3333 using widely accepted data and approaches:

- 3334 • Suitable data characteristics: Landsat-type data, for example, have been proven
3335 useful for national-scale land cover and land cover change assessments for
3336 minimal mapping units (MMU's) of about 1 ha. Temporal inconsistencies from
3337 seasonal variations that may lead to false change (phenology), and different
3338 illumination and atmospheric conditions can be reduced in the image selection
3339 process by using same-season images or, where available, applying two images
3340 for each time step.
- 3341 • Data quality: Suitable preprocessing quality for most regions is provided by some
3342 satellite data providers (i.e. global Landsat Geocover). Geolocation and spectral
3343 quality should be checked with available datasets, and related corrections are
3344 mandatory when satellite sensors with no or low geometric and radiometric
3345 processing levels are used.
- 3346 • Consistent and transparent mapping: The same cartographic and thematic
3347 standards (i. definitions), and accepted interpretation methods should be applied
3348 in a transparent manner using expert interpreters to derive the best national
3349 estimates. Providing the initial data, intermediate data products, a documentation
3350 of all processing steps interpretation keys and training data along with the final
3351 maps and estimates supports a transparent consideration of the monitoring
3352 framework applied. Consistent mapping also includes a proper treatment of areas
3353 with no data (ie. from constraints due to cloud cover).

3354 Considering the application of suitable satellite data and internationally agreed,
3355 consistent and transparent monitoring approaches, the accuracy assessment should
3356 focus on providing measures of thematic accuracy.

3357 **2.6.3.1.2 Accuracy assessment, area estimation of land cover change**

3358 Community consensus methods exist for assessing the accuracy of remote sensing-
3359 derived (single-date) land cover maps. The techniques include assessing the accuracy of
3360 a map based on independent reference data, and measures such as overall accuracy,
3361 errors of omission (error of excluding an area from a category to which it does truly
3362 belong, i.e. area underestimation) and commission (error of including an area in a
3363 category to which it does not truly belong, i.e. area overestimation) by land cover class,
3364 or errors analyzed by region, and fuzzy accuracy (probability of class membership), all of
3365 which may be estimated by statistical sampling.

3366

3367 While the same basic methods used for accuracy assessment of land cover can and
3368 should be applied in the context of land cover change, it should be noted that there are
3369 additional considerations. It is usually more complicated to obtain suitable, multi-
3370 temporal reference data of higher quality to use as the basis of the accuracy
3371 assessment; in particular for historical times frames. It is easier to assess land cover
3372 change errors of commission by examining areas that are identified as having changed.
3373 Because the change classes are often small proportions of landscapes and often
3374 concentrated in limited geographic areas, it is more difficult to assess errors of omission
3375 within the large area identified as unchanged. Errors in geo-location of multi-temporal
3376 datasets, inconsistent processing and analysis, and any inconsistencies in cartographic

3377 and thematic standards are exaggerated in change assessments. The lowest quality of
3378 available satellite imagery will determine the accuracy of change results. Perhaps, land
3379 cover change is ultimately related to the accuracy of forest/non-forest condition at both
3380 the beginning and end of satellite data analysis. However, in the case of using two single
3381 date maps to derive land cover change, their individual thematic error is multiplicative
3382 when used in combination if it may be assumed that the errors of one map are
3383 independent of errors in the other map (Fuller et al. 2003). Van Oort (2007) describes a
3384 method for computing an upper bound for change accuracy from accuracy of the single
3385 date maps but without assuming independence of errors at the two dates. These
3386 problems are known and have been addressed in studies successfully demonstrating
3387 accuracy assessments for land cover change (Lowell, 2001, Stehman et al., 2003). It
3388 should also be noted, that rather than compare independently produced maps from
3389 different dates to find change, it is almost always preferable to combine multiple dates of
3390 satellite imagery into a single analysis that identifies change directly. This subtle point is
3391 significant, as change is more reliably identified in the multi-date image data than
3392 through comparison of maps derived from individual dates of imagery.

3393 **2.6.3.1.3 Implementation elements for a robust accuracy assessment**

3394 For robust accuracy assessment of either land cover or land cover change, there are
3395 three principal steps for a statistically rigorous validation: sampling design, response
3396 design, and analysis design. An overview of these elements of an accuracy assessment
3397 are provided below, and full details of the community consensus "best practices" for
3398 these steps are provided in Strahler et al. (2006).

3399

3400 Sample design

3401 The sampling design is a protocol for selecting the locations at which the reference data
3402 are obtained. A probability sampling design is the preferred approach and typically
3403 combines either simple random or systematic sampling with cluster sampling (depending
3404 on the spatial correlation and the cost of the observations). Estimators should be
3405 constructed following the principle of consistent estimation, and the sampling strategy
3406 should produce accuracy estimators with adequate precision. The sampling design
3407 protocol includes specification of the sample size, sample locations and the reference
3408 assessment units (i.e. pixels or image blocks). Stratification should be applied in case of
3409 rare classes (i.e. for change categories) and to reflect and account for relevant gradients
3410 (i.e. ecoregions) or known factors influencing the accuracy of the mapping process.

3411

3412 Systematic sampling with a random starting point is generally more efficient than simple
3413 random sampling and is also more traceable. Sampling errors can be quantified with
3414 standard statistical formulas, although unbiased variance estimation is not possible for
3415 systematic sampling and conservative variance approximations are typically
3416 implemented (i.e. conservative in the sense that the estimated variance is higher than
3417 the actual variance). Non-sampling or "measurement" errors are more difficult to assess
3418 and require cross-checking actions (supervision on a sub-sample etc.).

3419

3420 Response design

3421 The response design consists of the protocols used to determine the reference or ground
3422 condition label (or labels) and the definition of agreement for comparing the map
3423 label(s) to the reference label(s). Reference information should come from data of higher
3424 quality, i.e. ground observations or higher-resolution satellite data. Consistency and
3425 compatibility in thematic definitions and interpretation is required to compare reference
3426 and map data.

3427 Analysis design

3428 The analysis design includes estimation formulas and analysis procedures for accuracy
3429 reporting. A suite of statistical estimates are provided from comparing reference and
3430 map data. Common approaches are error matrices, class specific accuracies (of
3431 commission and omission error), and associated variances and confidence intervals.

3432 **2.6.3.1.4 Use of Accuracy Assessment Results for Area Estimation**

3433 As indicated above, all maps derived from remote sensing include errors, and it is the
3434 role of the accuracy assessment to characterize the frequency of errors for each class.
3435 Each class may have errors of both omission and commission, and in most situations the
3436 errors of omission and commission for a class are not equal. It is possible to use this
3437 information on bias in the map to adjust area estimates and also to estimate the
3438 uncertainties (confidence intervals) for the areas for each class. Adjusting area
3439 estimates on the basis of a rigorous accuracy assessment represents an improvement
3440 over simply reporting the areas of classes as indicated in the map. Since areas of land
3441 cover change are significant drivers of emissions, providing the best possible estimates
3442 of these areas are critical.

3443

3444 A number of methods for using the results of accuracy assessments exist in the
3445 literature and from a practical perspective the differences among them are not
3446 substantial. One relatively simple yet robust approach is provided by Card (1982). This
3447 approach is viable when the accuracy assessment sample design is either simple random
3448 or stratified random. It is relatively easy to use and provides the equations for
3449 estimating confidence intervals for the area estimates, a useful explicit characterization
3450 of one of the key elements of uncertainty in estimates of GHG emissions.

3451 **2.6.3.1.5 Considerations for implementation and reporting**

3452 The rigorous techniques described in the previous section heavily rely on probability
3453 sampling designs and the availability of suitable reference data. Although a national
3454 monitoring system has to aim for robust uncertainty estimation, a statistical approach
3455 may not be achievable or practicable, in particular for monitoring historical land changes
3456 (i.e. deforestation between 1990-2000) or in many developing countries.

3457

3458 In the early stages of developing a national monitoring system, the verification efforts
3459 should help to build confidence in the approach. Growing experiences (i.e. improving
3460 knowledge of source and significance of potential errors), ongoing technical
3461 developments, and evolving national capacities will provide continuous improvements
3462 and, thus, successively reduce the uncertainty in the land cover and land-cover change
3463 area estimates. The monitoring should work backwards from a most recent reference
3464 point to use the highest quality data first and allow for progressive improvement in
3465 methods. More reference data are usually available for more recent time periods. If no
3466 thorough accuracy assessment is possible or practicable, it is recommended to apply the
3467 best suitable mapping method in a transparent manner. At a minimum, a consistency
3468 assessment (i.e. reinterpretation of small samples in an independent manner by regional
3469 experts) should allow some estimation of the quality of the observed land change. In this
3470 case of lacking reference data for land cover change, validating single date maps usually
3471 helps to provide confidence in the change estimates.

3472

3473 Information obtained without a proper statistical sample design can be useful in
3474 understanding the basic error structure of the map and help to build confidence in the
3475 estimates generated. Such information includes:

- 3476 • Spatially-distributed confidence values provided by the interpretation or
3477 classification algorithms itself. This may include a simple method by withholding a
3478 sample of training observations from the classification process and then using

3479 those observations as reference data. While the outcome is not free of bias, the
3480 outcomes can indicate the relative magnitude of the different kinds of errors likely
3481 to be found in the map.

- 3482 • Systematic qualitative examinations of the map and comparisons (both
3483 qualitative and quantitative) with other maps and data sources,
- 3484 • Systematic review and judgments by local and regional experts,
- 3485 • Comparisons with non-spatial and statistical data.

3486

3487 Any uncertainty bound should be treated conservatively, in order to avoid a benefit for
3488 the country (e.g. an overestimation of sinks or underestimation of emissions) based on
3489 highly uncertain data.

3490 For future periods, a statistically robust accuracy assessment should be planned from the
3491 start and included in the cost and time budgets. Such an effort would need to be based
3492 on a probability sample, using suitable data of higher quality, and transparent reporting
3493 of uncertainties. More detailed and agreed technical guidelines for this purpose can be
3494 provided by the technical community.

3495

3496 **2.6.3.2 Uncertainties in C stocks**

3497 Assessing uncertainties in the estimates of C stocks, and consequently of C stocks
3498 changes (i.e. the emission factor), can be more challenging than estimating uncertainties
3499 of the area and area changes (i.e. the activity data). This is particularly true for tropical
3500 forests, often characterized by a high degree of spatial variability and thus requiring
3501 resources to sample adequately to arrive at accurate and precise estimates of the C
3502 stocks in a given pool. Furthermore, whereas assessing separately random and
3503 systematic errors appears feasible for the activity data, it is far more difficult for the
3504 emission factor. Here we will briefly focus on the main potential sources of systematic
3505 errors, as these are likely the main sources of uncertainty in C stocks at national scale.

3506

3507 There are at least two important— and often unaccounted for —systematic errors that
3508 may increase the uncertainty of the emission factor. The first is related to completeness,
3509 i.e. which carbon pools are included. In this context, it is important to assess which pool
3510 is relevant for the purpose of REDD. To this aim, the concepts of “key categories” and
3511 “conservativeness” could greatly help in deciding which pool is worth to be measured,
3512 and at which level of accuracy it should be measured. The key category analysis as
3513 suggested by the IPCC (see section 2.2.4.1.1) allows identifying which pools in a given
3514 country are important or not. For example, depending on the organic carbon content of
3515 soil and the fate of the deforested land (converted to annual croplands or to perennial
3516 grasses) the soil may or may not be a significant source of GHG emissions (see section
3517 2.3 for further discussion). If the pool is significant, higher tiers methods (i.e. tier 2 or 3)
3518 should be used for estimating emissions, otherwise tier 1 may be enough. Furthermore,
3519 in some cases, neglecting soil carbon will cause a REDD estimate to be not complete, but
3520 nevertheless conservative (see section 4.4.1 for further discussion). Although
3521 conservativeness is, strictly speaking, an accounting concept, its consideration during
3522 the estimation phase may help in allocating resources in a cost-effective way.

3523

3524 The second potential source of systematic error is related to the representativeness of a
3525 particular estimate for a carbon pool. For example, the aboveground biomass of the
3526 forests in the deforested areas may be significantly different than country or ecosystem
3527 averaged values. Accurate estimates of carbon flux require not average values over large
3528 regions, but the biomass of the forests actually deforested and logged. However, once
3529 again, using sound statistical sampling methods, a country can design a plan to sample

3530 the forests undergoing or likely to undergo deforestation and degradation (see section
3531 2.2).

3532 **2.6.3.3 Identifying correlations**

3533 Correlation means dependency between parameters used in calculation as explained in
3534 section 2.6.2. Correlation can occur either between categories (for example the same
3535 emission factor used for different categories) or between years (e.g. same emission
3536 factor used for different years, or the same method with known bias used for area
3537 estimate in different years).

3538

3539 Regarding the correlation between different years, no correlation is typically assumed for
3540 activity data. For the emission factor, it depends on whether the same value of C stock
3541 change for the most disaggregated reported level is used across years or not: if different
3542 values are used, no correlation would be considered; by contrast, if the same emission
3543 factor is used (i.e. the same carbon stock change for the same type of conversion in
3544 different years) a perfect positive correlation would result. The latter case represents the
3545 basic assumption given by the IPCC (IPCC 2006) and by most LULUCF uncertainty
3546 analyses of Annex I parties (Monni et al 2007). If the REDD mechanism will foresee a
3547 comparison between emissions in different periods, i.e. between a reference emission
3548 level (totally or partially based on historical emissions from deforestation) and the
3549 emissions in the assessment period, a high or full correlation of C stock changes between
3550 periods could be a likely situation for most countries⁵⁰.

3551

3552 When the uncertainties are estimated for area and carbon stock change, potential
3553 correlations also have to be identified so that they can be dealt with when combining
3554 uncertainties. If Tier 1 method is used for combining uncertainties (i.e. "error
3555 propagation", see later), a qualitative judgment is needed whether correlations exist
3556 between years and categories. The correlations between years (in both area and carbon
3557 stock estimates) can be dealt with the equations of Tier 1 method. If correlations are
3558 identified between categories, it is good practice to aggregate the categories in a manner
3559 that correlations become less important (e.g. to sum up all the categories using the
3560 same EF before carrying out the uncertainty analysis). If a Tier 2 method is used for
3561 combining uncertainties (i.e. "Monte Carlo", see later), the correlations can be explicitly
3562 modeled.

3563 **2.6.3.4 Combining uncertainties**

3564 The uncertainties in individual parameters of can be combined using either (1) error
3565 propagation (IPCC Tier 1) or (2) Monte Carlo simulation (IPCC Tier 2). In both methods
3566 uncertainties can be combined regarding the level of emissions or removals (i.e.
3567 emissions or removals in a specific year) or trend of emissions or removals (i.e. change
3568 of emissions or removals between the two years).

3569

⁵⁰ The basic IPCC assumption of full correlation of emission factors uncertainties between years can be considered likely in the case of emissions from deforestation, primarily because, in many cases, no reliable data on C stock changes of past deforested areas exist in tropical countries. In other words, for each disaggregated reported level (e.g. tropical rain forest converted to cropland), it is likely that the same emission factor will be used both in the historical and in the assessment periods. However, a different situation may occur for forest degradation: in this case, the correlation will ultimately depend on how emissions are calculated, and potential correlations should be carefully examined.

3570 Tier 1 method is based on simple error propagation, and cannot therefore handle all
3571 kinds of uncertainty estimates. The key assumptions of Tier 1 method are:

- 3572 • estimation of emissions and removals is based on addition, subtraction and
3573 multiplication
- 3574 • there are no correlations across categories (or if there is, the categories are
3575 aggregated in a manner that the correlations become unimportant)
- 3576 • none of the parameters has an uncertainty higher than about ±60%
- 3577 • uncertainties are symmetric and follow normal distribution
- 3578 • relative ranges of uncertainty in the emission factors and area estimates are the
3579 same in years 1 and 2

3580

3581 However, even in the case that not all of the conditions are fulfilled, the method can be
3582 used to obtain approximate results. In the case of asymmetric distributions, the
3583 uncertainty bound the absolute value of which is higher should be used in the
3584 calculation.

3585

3586 Tier 2 method, instead, is based on Monte Carlo simulation, which is able to deal with
3587 any kind of models, correlations and distribution. However, application of Tier 2 method
3588 requires more resources than that of Tier 1.

3589

3590 Tier 1 level assessment

3591

3592 Error propagation is based on two equations: one for multiplication and one for addition
3593 and subtraction. Equation to be used in case of multiplication is (Equation 2.6.1):

$$3594 \quad U_{total} = \sqrt{U_1^2 + U_2^2 + \dots + U_n^2}$$

3595 Where:

3596 U_i = percentage uncertainty associated with each of the parameters

3597 U_{total} = the percentage uncertainty in the product of the parameters

3598

3599 Box 2.6.1 shows an example of the use of equation 2.6.1.

Box 2.6.1: Example of the use of Tier 1 method that combines uncertainty in area change and on the carbon stock (multiplication)

	Mean value	Uncertainty (% of the mean)
Area change (ha)	10827	8
Carbon stock (t C/ha)	148	15

Thus the total carbon stock loss over the stratum is:

$$10,827 \text{ ha} * 148 \text{ tC/ha} = 1,602,396 \text{ t C}$$

$$\text{And the uncertainty} = \sqrt{8^2 + 15^2} = \pm 17\%$$

In the case of addition and subtraction, for example when carbon stocks are summed up, the following equation will be applied (Equation 2.6.2):

$$U_{total} = \frac{\sqrt{(U_1 * x_1)^2 + (U_2 * x_2)^2 \dots (U_n * x_n)^2}}{|x_1 + x_2 \dots + x_n|}$$

Where:

U_i = percentage uncertainty associated with each of the parameters

x_i = the value of the parameter

U_{total} = the percentage uncertainty in the sum of the parameters

An example on the use of Equation 2.6.2 is presented in Box 2.6.2.

Box 2.6.2: Example of the use of Tier 1 method that combines carbon stock estimates (addition)

	Mean	95 % CI
	t (C/ha)	
Living Trees	113	11
Down Dead Wood	18	3
Litter	7	2

therefore the total stock is 138 t C/ha and the uncertainty =

$$\frac{\sqrt{(11\% * 113)^2 + (3\% * 18)^2 + (2\% * 7)^2}}{|113 + 18 + 7|} = \pm 9\%$$

The total uncertainty is $\pm 9\%$ of the mean total C stock of 138 t C/ha

3628 Tier 1 trend assessment

3629

3630 Estimation of trend uncertainty following the IPCC Tier 1 method is based on the use of
3631 two sensitivities:

3632

3633 • Type A sensitivity, which arises from uncertainties that affect emissions or
3634 removals in the years 1 and 2 equally (i.e. the variables are correlated across the
3635 years)

3636 • Type B sensitivity which arises from uncertainties that affect emissions or
3637 removals in the year 1 or 2 only (i.e. variables are uncorrelated across the years)

3638

3639 The basic assumption is that emission factors and other parameters are fully correlated
3640 across the years (Type A sensitivity). Activity data, on the other hand, is usually
3641 assumed to be uncorrelated across years (Type B sensitivity). However, this association
3642 will not always hold and by modifying the calculation, it is possible to apply Type A
3643 sensitivities to activity data, and Type B sensitivities to emission factors to reflect
3644 particular circumstances. Type A and Type B sensitivities are simplifications introduced
3645 for the approximate analysis of correlation. To get more accurate results or to be able to
3646 handle correlations explicitly, Tier 2 method would be needed.

3647

3648 Table 2.6.1 can be used to combine level and trend the uncertainties using the Tier 1
3649 method. The emissions and removals of each category in the years 1 and 2 are entered
3650 into columns C and D, and the respective percentage uncertainties expressed with the
3651 95% confidence interval are entered into columns E and F. For the rest of the columns,
3652 the equations are entered as shown in the table. The letters (for example 'C') denote the
3653 entries in the same row and respective column, whereas the sums (for example 'ΣC')
3654 denote the sum of all the entries in the respective column. The level and trend
3655 uncertainties are calculated in the last row of the table.

3656

3657

3658 **Table 2.6.1. Tier 1 calculation table** (based on IPCC method)

3659

A	B	C	D	E	F	G	H	I	J	K	L	M
Category	Gas	Emissions or removals in year 1	Emissions or removals in year 2	Area uncertainty	Emission factor uncertainty	Combined uncertainty	Contribution to variance by category in year 2	Type A sensitivity	Type B sensitivity	Uncertainty in trend introduced by emission factor uncertainty (Note ii)	Uncertainty in trend introduced by area uncertainty (Note iii)	Uncertainty introduced to the trend in total emissions/
		Mg CO ₂	Mg CO ₂	%	%	$\sqrt{E^2 + F^2}$	$\frac{(G * D)^2}{(\sum D)^2}$	Note i	$\frac{D}{\sum C}$	$I * F$	$J * E * \sqrt{2}$	$K^2 * L^2$
E.g. Forest converted to Cropland	CO ₂											

E.g. Forest converted to Grassland	CO ₂											
Etc	...											
Total		$\sum C$	$\sum D$				$\sum H$					$\sum M$
					Level uncertainty		$\sqrt{\sum H}$				Trend uncertainty	$\sqrt{\sum M}$

3660

3661 Note i:
$$\left| 100 * \frac{0.01 * D + \sum D - (0.01 * C + \sum C)}{0.01 * C + \sum C} - 100 * \frac{\sum D - \sum C}{\sum C} \right|$$

3662 Note ii: The equation assumes full correlation between the emission factors in the years 1 and 2. If it is
 3663 assumed that no correlation occurs, the following equation is to be used: $J * F * \sqrt{2}$

3664 Note iii: The equation assumes no correlation between the area estimates in the years 1 and 2. If it is
 3665 assumed that full correlation occurs, the following equation is to be used: $I * E$

3666

3667 Tier 2 Monte Carlo simulation

3668

3669 The Tier 2 method is a Monte Carlo type of analysis. It is more complicated to apply, but
 3670 gives more reliable results particularly where uncertainties are large, distributions are
 3671 non-normal, or correlations exist. Furthermore, Tier 2 method can be applied to models
 3672 or equations, which are not based only on addition, subtraction and multiplication. See
 3673 Chapter 5 of IPCC GPG LULUCF for more details on how to implement Tier 2.

3674

3675 **2.6.3.5 Reporting and documentation**

3676 According to the IPCC, it is good practice to report the uncertainties using a standardized
 3677 format. For the purpose of this Sourcebook, we present a slightly simplified version of
 3678 the IPCC table (Table 2.6.2). Columns A to G are the same as in Table 2.6.2 if Tier 1
 3679 method is used. Column H will be calculated according to the equation given, whereas
 3680 the entries in column I will be calculated by category following the same method as in
 3681 the calculation of the total trend uncertainty. Column J is for additional information on
 3682 the methods used.

3683

3684 **Table 2.6.2. Reporting table for uncertainties.**

3685

A	B	C	D	E	F	G	H	I	J
Category	Gas	or Emissions removals in year 1	or Emissions removals in year 2	Area uncertainty	Emission factor uncertainty	Combined uncertainty	Inventory trend for year 2 increase with respect to year 1 (Note a)	Trend uncertainty of the category	Method used to estimate uncertainty (Note b)
		Mg CO ₂	Mg CO ₂	%	%	%	% of year 1		
E.g. Forest Land converted to Cropland	CO ₂								
E.g. Forest Land converted to Grassland	CO ₂								
Etc	...								
Total						Level uncertain ty		Trend uncertain ty	

3686

3687 Note a:
$$\frac{D - C}{C}$$

3688 Note b: For example: expert judgment, literature, statistical techniques for sampling, information on the
3689 instrument used

3690

3691 **2.6.4 Key References for Section 2.6**

3692

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3719

3720

3721 **2.7 STATUS OF EVOLVING TECHNOLOGIES**

3722

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3724 Sandra Brown, Winrock International, USA

3725 Michael Falkowski, University of Idaho, USA

3726 Scott Goetz, Woods Hole Research Center, USA

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3732 Michael Wulder, Canadian Forest Service, Canada

3733 **2.7.1 Scope of Chapter**

3734 The methods describe in chapters 2.1 to 2.5 provide readily available approaches to
3735 estimate and report on carbon emissions from deforestation and forest degradation
3736 following the IPCC guidance; with emphasis on the historical period. In addition, new
3737 technologies and approaches are being developed for monitoring changes in forest area,
3738 forest degradation and carbon stocks. In this section they are described as evolving data
3739 sources and technologies given the following considerations:

- 3740 • The approaches have been demonstrated for in project studies, and, thus, are
3741 potentially useful and appropriate for REDD implementation but have not been
3742 operationally used for forest/carbon stock change monitoring on the national level
3743 for carbon accounting and reporting purposes,
- 3744 • They may provide data and certainty in addition to the approach described in
3745 chapters 2.1 to 2.5, i.e. to overcome known limitations of optical satellite data in
3746 persistently cloudy parts of the tropics,
- 3747 • Data and approaches may not be available for all developing country areas
3748 interested in REDD,
- 3749 • Implementation usually requires an additional amount of resources (i.e. cost,
3750 national monitoring capacities etc.),
- 3751 • Further pilot cases and international coordination are needed to further test and
3752 implement these technologies in a REDD context,
- 3753 • Their utility may be enhanced in coming years depending on data acquisition,
3754 access and scientific developments,

3755

3756 The intention here is not to describe the suite of evolving technologies in all detail. The
3757 discussions should build awareness of these techniques, provide basic background
3758 information and explain their general approaches, potentials and limitations. The options
3759 to eventually use them for national forest monitoring activities would depend on specific
3760 country circumstances.

3761

3762 **2.7.2 Role of LIDAR observations**

3763 **2.7.2.1 Background and characteristics**

3764 LIDAR (LIght Detection And Ranging) sensors use lasers to directly measure the three-
3765 dimensional distribution of vegetation canopies as well as sub-canopy topography,
3766 resulting in accurate estimates of both vegetation height and ground elevation
3767 (Boudreau et al., 2008). Of especial interest for REDD monitoring, LIDAR is the only
3768 remote sensing technology to provide measures that have demonstrated a non-
3769 asymptotic relationship with biomass (Drake et al., 2003). LIDAR systems are classified
3770 as either discrete return or full waveform sampling systems, and may further be
3771 characterized by whether they are profiling systems (i.e., recording only along a narrow
3772 transect), or scanning systems (i.e., recording across a wider swath). Full waveform
3773 sampling LIDAR systems generally have a more coarse horizontal spatial resolution (i.e.,
3774 a large footprint: 10 – 100 m) combined with a fine and fully digitized vertical spatial
3775 resolution, resulting in full sub-meter vertical profiles. Full waveform LIDARs are
3776 generally profiling systems and are most commonly used for research purposes.
3777 Although there are currently no systems that provide large-footprint full waveform
3778 LIDAR data commercially, the Geoscience Laser Altimeter System (GLAS) onboard the
3779 NASA Ice, Cloud and land Elevation Satellite (ICESat) is a large-footprint full waveform
3780 LIDAR system that may be used for forest characterization and for the development of
3781 generalized products for modeling (Næsset, 2002). For example, data from GLAS is
3782 currently being used to derive forest canopy height and aboveground biomass for the
3783 globe. The GLAS sensor has a horizontal footprint of ~65 m with an along-track post
3784 spacing of 172 m, and a maximum across-track post spacing of 15 km at the equator.
3785 The third and final laser on ICESat I / GLAS failed on October 19, 2008, but the ICESat
3786 team is, as of October/November 2008, attempting to restart laser 2. If it can be
3787 restarted, GLAS will continue to take spring/fall measurements until laser failure

3788

3789 Discrete return LIDAR systems (with a small footprint size of 0.1 – 2 m) typically record
3790 one to five returns per laser footprint and are optimized for the derivation of sub-meter
3791 accuracy terrain surface elevations. These systems are used commercially for a wide
3792 range of applications including topographic mapping, power line right-of-way surveys,
3793 engineering, and natural resource characterization. Discrete return scanning LIDAR
3794 yields a three-dimensional cloud of points, with the lower points representing the ground
3795 and the upper points representing the canopy. One of the first steps undertaken when
3796 processing LIDAR data involves the separation of ground versus non-ground (i.e.,
3797 canopy) hits—a function that is often undertaken by LIDAR data providers using software
3798 such as TerraScan, LP360, or the data provider's own proprietary software. Analysis can
3799 commence once all LIDAR points have been classified into ground or non-ground returns.
3800 Ground hits are typically gridded to produce a bare earth Digital Elevation Model (DEM)
3801 using standard software approaches such as triangulated irregular networks, nearest
3802 neighbour interpolation, or spline methods. As the point spacing of the LIDAR
3803 observations is significantly finer than the spatial detail typically observable on aerial
3804 photography, the DEMs generated from LIDAR often contain significantly more horizontal
3805 and vertical resolution than elevation models generated from moderate scale aerial
3806 photography (Lim et al., 2003).

3807

3808 **2.7.2.2 Experiences for monitoring purposes**

3809 To date, research and development activities have focused upon using LIDAR as tool for
3810 characterizing vertical forest structure - primarily the estimation of tree and stand
3811 heights, with volume, biomass, and carbon also of interest. With increasing availability
3812 of LIDAR data, forest managers have seen opportunities for using LIDAR to meet a wider
3813 range of forest inventory information needs. For instance, height estimates generated

3814 from airborne remotely sensed LIDAR data have been found to be of similar, or better
3815 accuracy than corresponding field-based estimates and studies have demonstrated that
3816 the LIDAR measurement error for individual tree height (of a given species) is less than
3817 1.0 m and less than 0.5 m for plot-based estimates of maximum and mean canopy
3818 height with full canopy closure. Additional attributes, such as volume, biomass, and
3819 crown closure, are also well characterized with LIDAR data.

3820

3821 Scanning LIDAR is typically used to collect data with a full geographical coverage ("wall-
3822 to-wall") of the area of interest. Forest inventory providing detailed information of
3823 individual forest stands for planning and management purposes is rapidly increasing to
3824 become a standard method for forest inventory of territories with a size of 50-50,000
3825 km². Scanning LIDAR technology is currently being used or tested globally for
3826 operational inventory, pre-operational trials, or to generate project specific sub-sets of
3827 forest attributes (including biomass).

3828

3829 A basic requirement for inventory and monitoring of forest resources and biomass is the
3830 availability of ground measurement using conventional field plots. Ground measurements
3831 are required to establish relationships between the three-dimensional properties of the
3832 LIDAR point cloud (e.g. canopy height and canopy density) and the target biophysical
3833 properties of interest, like for example biomass, using parametric or nonparametric
3834 statistical techniques. Once such relationships have been established, the target
3835 biophysical properties can be predicted with high accuracy for the entire area of interest
3836 for which LIDAR data are available.

3837

3838 For monitoring of larger territories, like provinces, nations or even across nations, such a
3839 two-stage procedure can even be used in a sampling mode, where the airborne LIDAR
3840 instrument is used as a sampling device. Optical remotely sensed imagery and other
3841 spatial data can be used to aid in stratification, supporting sampling guidance and
3842 subsequent estimation. Profiling as well as scanning LIDAR instruments can be flown
3843 along strips separated by many kilometers, depending on the desired sampling
3844 proportion. Thus, the LIDAR data can be used to provide a conventional sampling-based
3845 statistical estimate of biomass or changes in amount of biomass over time. A sample of
3846 conventional ground plots of a nation may for example cover on the order of 0.0003% of
3847 the entire population in question (assuming a 10×10 km² spacing between plots with size
3848 300 m²), whereas a sample of scanning LIDAR data collected along strips flown over the
3849 same field plots will constitute a sample of 5-10% of the population. Because biomass
3850 and canopy properties derived from LIDAR data are highly correlated, LIDAR combined
3851 with field data has been demonstrated to improve the measurement efficiency and to
3852 improve accuracy and/or reduce costs (in comparison to field based measures).
3853 Sampling with profiling LIDAR was demonstrated in Delaware (~5,000 km²), USA, a few
3854 years ago. By introducing a third stage, i.e., LIDAR data from satellite (ICESat/GLAS),
3855 and combining these data with airborne profiling LIDAR and field data, it has been shown
3856 that fairly large territories can be sampled with lasers for biomass estimation. Recently,
3857 estimates of biomass and carbon stocks were provided for the entire province of Quebec
3858 (~1,270,000 km²), Canada. A parallel development of the technical procedures and a
3859 statistical framework is now taking place and being demonstrated for scanning LIDAR in
3860 Hedmark County (~25,000 km²), Norway.

3861

3862 Demonstrations of biomass assessment over larger areas of in tropical forest have so far
3863 not taken place. However, a number of experiments with airborne LIDAR in tropical
3864 forest have shown that there exist strong relationships between biomass (and other
3865 biophysical properties) and LIDAR data. Unlike other remote sensing techniques, such as
3866 optical remote sensing and SAR, LIDAR does not suffer from saturation problems
3867 associated with high biomass values. LIDAR has proven to be capable of discriminating

3868 between biomass values up to $>1,300 \text{ Mg ha}^{-1}$. Thus, airborne and spaceborne LIDAR
3869 are likely to have great potentials as sampling tools, especially in tropical forests.

3870

3871 Monitoring costs when using airborne LIDAR are variable. In general, users can expect
3872 some elements of the costing structure to be similar to air photo acquisition, including
3873 flying time and related fuel costs. Further, economies of scale are also to be considered,
3874 whereby larger project areas can lead to a reduction in per unit area costs. Large
3875 acquisition areas also mean less time is spent turning the aircraft and more time actually
3876 acquiring data. Reported costs for LIDAR surveys vary widely, but lower costs per
3877 hectare can be expected for larger projects. Processing to meet project specific
3878 information needs will also result in additional costs. In Europe, comparable costs for
3879 LiDAR data collection in operational forest inventory are at the moment $<\$0.5\text{-}1.0$ per
3880 hectare when the projects are of a certain size. Prices in South America using local data
3881 providers (e.g. Brazilian companies) are typically higher. The situation is likely to be the
3882 same in Africa using local data providers (e.g. South African data providers). Recent bids
3883 for a REDD demonstration in Tanzania from European data providers indicate prices for
3884 "wall-to-wall" LIDAR data acquisition on the order of $\$0.5\text{-}1.0$ per hectare. However,
3885 when LIDAR is used to sample a landscape, say a territory on the order of $1,000,000$
3886 km^2 , a marginal cost per km flight line of $\sim\$30\text{-}40$ can be anticipated in (e.g., eastern
3887 Africa). Thus, by a sampling proportion of for example 1% and a swath width of 1 km, it
3888 should be feasible to sample a $1,000,000 \text{ km}^2$ landscape for a total cost of about
3889 $\$300,000\text{-}400,000$.

3890 **2.7.2.3 Area of contribution to existing IPCC land sector reporting**

3891 Ground plot information is an important component of most monitoring schemes
3892 including those focused on REDD. LIDAR derived measures can work in an integrated
3893 fashion with ground-based surveys; whereby, ground plots can be used to calibrate and
3894 validate LIDAR measures, and attributes emulating ground bases measures can be
3895 derived from the LIDAR data, ultimately increasing the overall sample size. In this way,
3896 LIDAR offers opportunities for an alternative method of field measurement. Degradation
3897 of forests in many cases is difficult to detect and characterize. Optical remotely sensed
3898 data is a key data source for capturing change and can be related to degradation. Since
3899 LIDAR captures the vertical distribution and structure of forests, integrating LIDAR with
3900 optical remotely sensed change data can be used to indicate the carbon consequences of
3901 the changes present.

3902

3903 LIDAR has both high vertical and horizontal resolutions affording fine, field plot-like
3904 measures to be made. These fine-scale measures can be used to emulate ground data,
3905 to calibrate and validate model outcomes, to inform on the carbon consequences of
3906 deforestation and degradation, and to locate and enable characterization of forest gaps
3907 introduced over time. The context and information needs of REDD must be considered
3908 when aiming to determine the utility of LIDAR measurements (including the value of
3909 increased accuracy and precision of measures and / or the ability to better characterize
3910 error budgets associated with mapped or estimated measures).

3911

3912 **2.7.2.4 Data availability and required national capacities**

3913 Both air- and space-borne data are available. The airborne data source can be
3914 considered globally available, with coverage on-demand, procured via contracting with
3915 commercial agencies on a global basis. While LIDAR data is broadly available, the
3916 applications uses are more focused on utility corridor characterization and elevation
3917 model development. Operational forest characterization is less common, typically
3918 requiring field support and custom algorithms. Spaceborne LIDAR is also available
3919 globally, with a number of caveats. NASA is supporting the production of global

3920 information products based upon GLAS information that provide an insight into the on-
3921 going and future utility of spaceborne LIDAR data.

3922

3923 The national capacity to utilize LIDAR data can be high when analysis from data capture
3924 through to information generation is desired; conversely, capacity needs can be lower if
3925 a contract-based approach is pursued. National end users can contract the desired
3926 information outcomes from the LIDAR acquisition and processing. As such, it is
3927 important to have clear information needs that can be used to develop statements of
3928 work and deliverables for contractors. Information needs to meet REDD criteria can be
3929 developed for LIDAR data analogous to those under development for field data.

3930

3931 **2.7.2.5 Status, expected near-term developments and long-term sustainability**

3932 Unless laser 2 on board ICESat I / GLAS can be restarted, there will be no operational
3933 space laser available over the next few years. However, the United States is working
3934 toward the development of three new spaceborne LIDAR missions; ICESat II, DESDynI
3935 (Deformation, Ecosystem Structure, and Dynamics of Ice), and LIST (Laser Imaging for
3936 Surface Topography). Although specific mission details are dynamic, it is expected that
3937 ICESat II will be launched in 2015 with data acquisition parameters similar to ICESat I
3938 (single beam waveform profiler, 30-50 m footprint, and ~140 m along-track post
3939 spacing). Assuming a launch date of 2015, there will likely be a 6-7 year data gap
3940 between the ICESat I and ICESat II missions. The DESDynI and LIST missions will
3941 commence at a later date, i.e., ca 2017 and 2020, respectively. DESDynI will be a dual
3942 sensor platform (multibeam LIDAR and L-band radar) that acquires LIDAR data with
3943 footprints of ~25 m with along- and cross-track profile spacing of 25-30 m and 2-5 km,
3944 respectively. The LIST platform is expected to collect global wall-to-wall LIDAR data over
3945 a 5 year mission. LIDAR data acquired by LIST will have a footprint size and along and
3946 across-track posting of 5 m. Although there will be a data gap, the current ICESat I
3947 platform in conjunction with the proposed ICESat II platform are likely to provide LIDAR
3948 data collected in a systematic manner across the globe.

3949

3950 **2.7.2.6 Applicability of LIDAR as an appropriate technology**

3951 While LIDAR may be considered as an emerging technology in terms of large-area
3952 monitoring especially with the nascent REDD processes, LIDAR is well established as a
3953 data source for meeting forest management and science objectives. The capacity for
3954 LIDAR to characterize biomass and change in biomass over time positions the technology
3955 well to meet REDD information needs. LIDAR data in terms of information content are
3956 analogous to field based measures. As such, LIDAR may be considered as a source of
3957 sampled information, while is also uniquely able to produce detailed information over
3958 large areas. The information need and the actual monitoring framework utilized may
3959 further guide the applicability of LIDAR for national carbon accounting and reporting
3960 purposes. The ability to estimate uncertainty measures from LIDAR data also positions
3961 the technology well to produce transparent and verifiable measures in support of
3962 accounting and reporting activities. While costs need to be considered, these actual costs
3963 to a program need to be vetted against the information that is being developed, how this
3964 information meets the specified needs, and importantly, how the reduction in uncertainty
3965 from LIDAR offsets initial costs. Pilot studies and some international coordination of on-
3966 going and proposed activities to meet REDD information needs are encouraged. While
3967 LIDAR data are currently available in a limited manner from spaceborne platforms, an
3968 increase in this capacity is envisioned and encouraged. The possible limitations in
3969 spaceborne measures are well offset by the widespread and operational acquisition of
3970 LIDAR from airborne platforms. Airborne LIDAR data collected by commercial providers

3971 fosters - global availability and enables national capacities to be aided by delivery of
3972 products rather than raw data.

3973

3974 **2.7.3 Forest monitoring using Synthetic Aperture Radar (SAR)** 3975 **observations**

3976 **2.7.3.1 Synthetic Aperture Radar technology**

3977 Synthetic Aperture Radar (SAR) sensors have been used since the 1960s to produce
3978 remote sensing images of earth-surface features based on the principals of radar (radio
3979 detection and ranging) reflectivity. Over the past two decades, the science and
3980 technology underpinning radar remote sensing has matured considerably. Additionally,
3981 high-resolution global digital elevation models (e.g., from the 2000 Shuttle Radar
3982 Topography Mission, SRTM), which are required for accurate radar calibration and image
3983 geolocation, are now freely available. Together, these advancements have enabled and
3984 encouraged the development and operational deployment of advanced spaceborne
3985 instruments that now make systematic, repetitive, and consistent SAR observations of
3986 tropical forest cover possible at regional to global scales.

3987

3988 Radar remote sensors complement optical remote sensors in two fundamental ways.
3989 First, where as optical sensors passively record electromagnetic energy (e.g., sun light)
3990 radiated or reflected by earth-surface features, radar is an active system, meaning it
3991 serves as the source of its own electromagnetic energy. As a radar sensor orbits the
3992 Earth, it transmits short pulses of energy toward the surface below, which interact with
3993 surface features such as forest vegetation. A portion of this energy is reflected back
3994 toward the sensor where the backscattered signal is recorded. Second, while optical
3995 sensors operate primarily in the visible and infrared (ca. 0.4-15.0 μm) portions of the
3996 electromagnetic spectrum, radar sensors operate in the microwave region (ca. 3-70 cm).
3997 Where as short electromagnetic waves in the visible and infrared range are readily
3998 scattered by atmospheric particulates (e.g., haze, smoke, and clouds), long-wavelength
3999 microwaves generally penetrate through them, making radar remote sensing an
4000 invaluable tool for imaging tropical forests which are commonly covered by clouds.
4001 Moreover, microwaves penetrate into forest canopies, with the amount of backscattered
4002 energy dependant in part on the three-dimensional structure and moisture content of the
4003 constituent leaves, branches and stems, and underlying soils, thus resulting in useful
4004 information on forest structural attributes including structural forest cover type and
4005 aboveground biomass. Thereby, the degree to which microwave energy penetrates into
4006 forest canopies depends on the frequency/wavelength of the incoming electromagnetic
4007 waves. Generally speaking, incoming microwaves are scattered most strongly by
4008 surface elements (e.g., leaves, branches, and stems) that are large relative to the
4009 wavelength. Hence, longer wavelengths (e.g., P-/L-band) penetrate deeper into forest
4010 canopies than shorter wavelengths (e.g., C-/X-band). In addition to wavelength, the
4011 polarization of the transmitted and received microwave energy provides additional
4012 sensitivity with which to characterize forest structure.

4013

4014 An increasing number of SAR sensors are now being built with polarimetric and high-
4015 resolution capabilities following recent advancements in SAR data recording and
4016 computer processing. The first civilian spaceborne SAR sensors are now being operated
4017 at spatial resolutions finer than 5 meters (e.g., TerraSAR-X, Cosmo SkyMed, etc.), which
4018 is of great potential for example where the mapping of logging roads and associated
4019 forest degradation patterns is concerned. A listing of past, current, and future SAR
4020 sensors is included in Table 2.7.1. In addition to the sensors listed in Table 2.7.1, a
4021 number of follow on missions are planned to ensure continuity beyond 2010. In

4022 summary, radar remote sensing is well suited to potentially support tropical forest
 4023 monitoring needs.

4024

4025 **Table 2.7.1: Summary of current and planned spaceborne synthetic aperture**
 4026 **radar (SAR) sensors and their characteristics.**

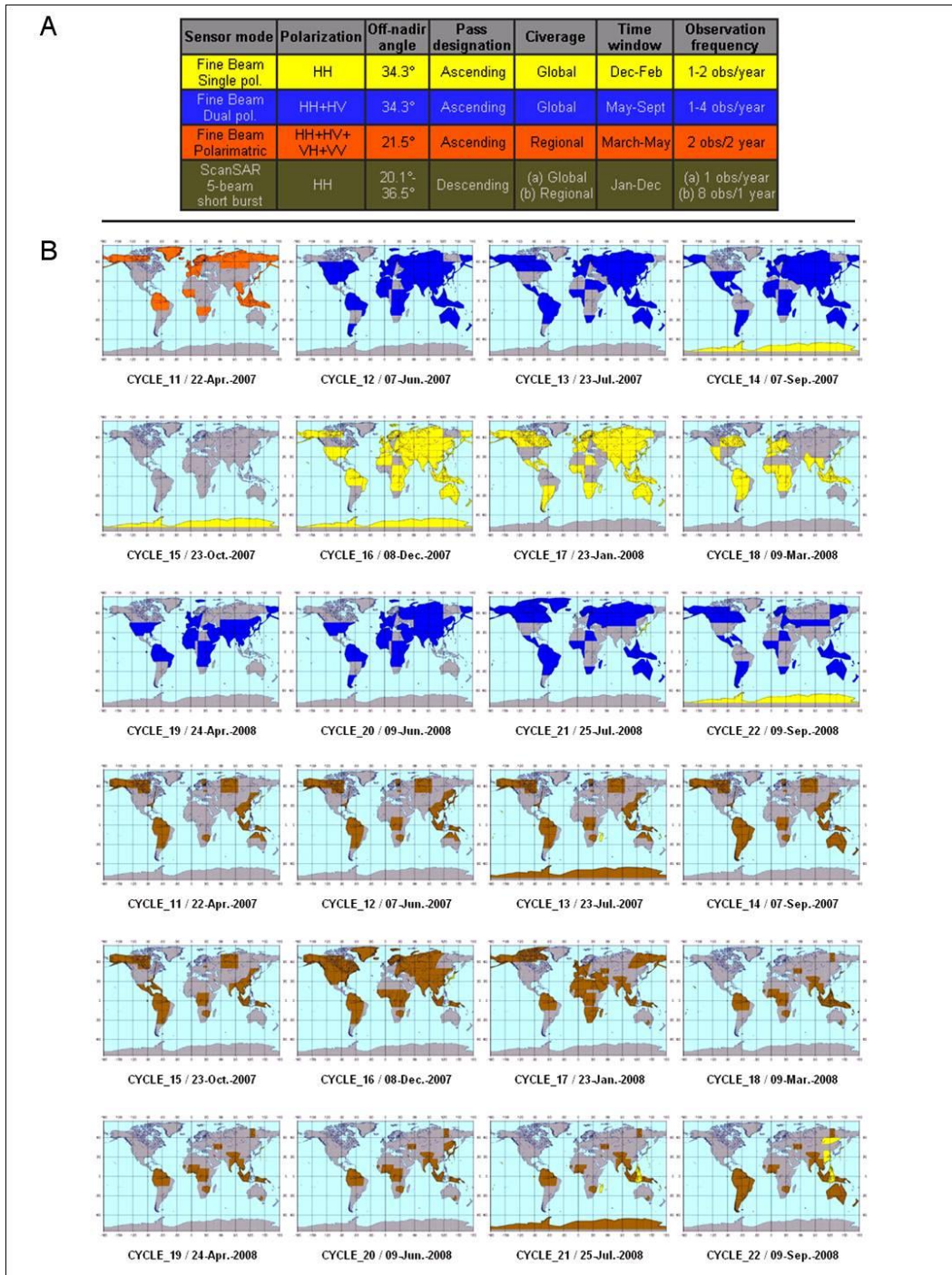
Current Satellites/sensors	Nation(s)	Period of Operation	Band	Polarization	Spatial Resolution (m)	Orbital Repeat (days)
ERS-1	Europe	1991-2000	C	Single (VV)	26	3-176
JERS-1	Japan	1992-1998	L	Single (HH)	18	44
ERS-2	Europe	1995-	C	Single (VV)	26	35
RADARSAT 1	Canada	1995-	C	Single (HH)	8-100	3-24
Envisat/ASAR	Europe	2002-	C	Single, Dual	30-1000	35
ALOS/PALSAR	Japan	2006-	L	Single, Dual, Quad	10-100	46
RADARSAT 2	Canada	2007-	C	Single, Dual, Quad	3-100	24
TerraSAR-X	Germany	2007-	X	Single, Dual, Quad	1-16	11
COSMO- SkyMed	Italy	2007-	X	Single, Dual Interferometric	1-100	16

4027

4028

4029

4030



4031

4032

4033 **Figure 2.7.1: (A) Global observation strategy for (B) various ALOS/PALSAR**
 4034 **sensor modes.** The systematic observation strategy is likely to be repeated throughout
 4035 mission life, projected to last beyond 2016 (source: JAXA/EORC).

4036

4037 While satellites carrying SAR sensors have been in orbit since the early 1990s (Table
 4038 2.7.1), the pan-tropical observation of forest structure by radar remote sensing received
 4039 a further support as of January 24, 2006, when the Japanese Aerospace Exploration
 4040 Agency (JAXA) launched their newest spaceborne Earth observing platform, the
 4041 Advanced Land Observing Satellite (ALOS) featuring PALSAR (Phased Array L-band
 4042 Synthetic Aperture Radar), the first polarimetric L-band imaging radar sensor ever
 4043 deployed on a satellite platform for civilian Earth observation. The ALOS mission is
 4044 particularly unique in that a dedicated global data observation strategy was designed

4045 with the goal of systematically imaging all of Earth's land masses in a wall-to-wall
4046 manner at least once per year at 10 m, 20 m, and 100 m resolution (Figure 2.7.1). In
4047 the interest of producing globally-consistent radar image datasets of the type first
4048 generated by the Japanese Earth Resources Satellite (JERS-1) during the Global Rain
4049 Forest Mapping (GRFM) project of the mid-1990s, an international ALOS "Kyoto and
4050 Carbon Science Team" was formed to develop an acquisition strategy to support global
4051 forest monitoring needs. This strategy is currently fixed, and will very likely continue
4052 through the lifetime of the mission, which is expected to last at least 10 years, spanning
4053 much if not all of the post-Kyoto commitment period of 2013 to 2017. A number of
4054 space agencies including JAXA, the European Space Agency (ESA), and the U.S. National
4055 Aeronautics and Space Administration (NASA) now have plans to deploy additional
4056 imaging radar sensors that are scheduled to become operational over the next 5-7 years
4057 (Table 2.7.1), ensuring the long-term continuity of repeat observations at L-band and
4058 other radar frequencies. Overall, these sensor characteristics make ALOS/PALSAR data
4059 ideally suited to complement the existing fleet of Earth remote sensing platforms by
4060 providing high-resolution, wall-to-wall, image coverage that is acquired over short time
4061 frames and unimpeded by cloud cover.

4062

4063 **2.7.3.2 Case Study: Xingu River Headwaters, Mato Grosso, Brazil**

4064 Given the excellent positional accuracy (~9.3 m) of ALOS/PALSAR data and the recent
4065 availability of advanced radar image processing methods, regional- to continental-scale
4066 image mosaics can be readily produced for any location that has been systematically
4067 imaged by the ALOS/PALSAR sensor. Figure 2.7.2 includes shows a large-area (ca.
4068 400,000 km²) image mosaic of ALOS/PALSAR data, which covers the headwaters of the
4069 Xingu River, in Mato Grosso, Brazil. Data were acquired between June 8th and July 27th,
4070 2007, as part of a 4-month global acquisition (see Figure 2.7.1). This particular mosaic
4071 was generated in less than one week using two distinct (i.e., dual-polarimetric) PALSAR
4072 information channels: 1) image data derived from microwave energy that was both
4073 transmitted and received by the PALSAR antenna in the horizontal direction (i.e. parallel
4074 to Earth's surface), and b) image data derived from microwave energy transmitted in the
4075 horizontal direction, but received in the vertical direction (i.e., perpendicular to the
4076 Earth's surface). The former case is referred to as HH-polarization while the latter case is
4077 referred to as HV-polarization. The concept of polarization is an important aspect of
4078 radar remote sensing because earth-surface features such as forest canopies respond
4079 differently to different polarizations.

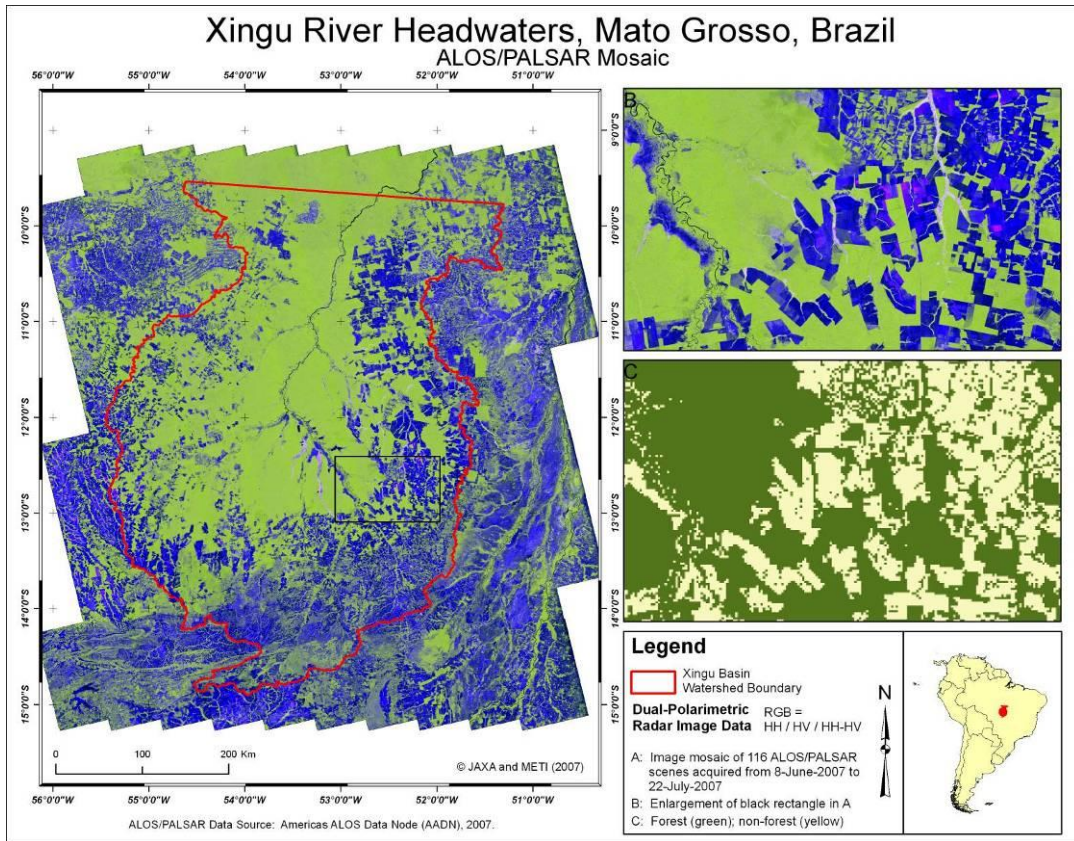
4080

4081 Because radar sensors are "active" remote sensing systems (i.e., they transmit and
4082 receive their own microwave energy, and thus complement "passive" optical sensors
4083 which measure reflected sun light), radar images are always visual representations (i.e.,
4084 displayed in the visible spectrum) of microwave energy received at and recorded by the
4085 sensor. Single radar information channels are typically displayed as grayscale images.
4086 When interpreting a radar image it is a general rule of thumb that increasing brightness
4087 corresponds to a greater amount of energy recorded by the sensor. Applying this rule of
4088 thumb to the interpretation of vegetated regions in an ALOS/PALSAR image, areas with a
4089 greater amount of vegetation biomass of a given structural type will appear brighter due
4090 to the greater amount of energy scattered back to and recorded by the sensor. If
4091 multiple radar information channels (i.e., multiple polarizations) are available, color
4092 images can be generated by assigning specific channels or combinations of channels to
4093 each of the visible red, green, and blue (RGB) channels commonly used for display in
4094 computer monitors. To create the color (RGB) image displayed in Figure 2.7.2, the HH
4095 channel was assigned the color red, the HV channel was assigned the color green, and
4096 the difference between the two (HH minus HV) was assigned the color blue. Hence,
4097 green and yellow image tones correspond to instances where both HH and HV
4098 information channels have high energy returns (e.g., over forested and urban areas).
4099 Blue and magenta tones are generally found in non-forested (e.g., agricultural) areas

4100 where HH-polarized energy tends to exhibit higher returns from the surface than does
4101 HV-polarized energy. The information contained in the three ALOS/PALSAR image
4102 channels has recently been used to demonstrate the utility of these data for accurate
4103 large-area, forest/non-forest mapping. Ground validation in this area demonstrated that
4104 an overall classification accuracy of greater than 90% was achieved from the ALOS radar
4105 imagery.

4106

4107



4108

4109

4110 **Figure 2.7.2:** Xingu River headwaters, Mato Grosso, Brazil. The radar image mosaic is
4111 a composite of 116 individual scenes (400,000 km²) acquired by the PALSAR sensor
4112 carried on board ALOS. A preliminary land cover classification has been generated with
4113 an emphasis on producing an accurate forest/nonforest map. In the forested areas, the
4114 sensitivity of the PALSAR data to differences in aboveground biomass is also being
4115 investigated in collaboration with the Amazon Institute of Environmental Research
4116 (IPAM). Data by JAXA/METI and American ALOS Data Node. Image processing and
4117 analysis by The Woods Hole Research Center, 2007.

4118

4119 **2.7.4 Integration of satellite and in situ data for biomass mapping**

4120 The advantage of biomass estimation approaches that incorporate some form of
4121 remotely sensed data is through provision of a synoptic view of the area of interest,
4122 thereby capturing the spatial variability in the attributes of interest (e.g., height, crown
4123 closure). The spatial coverage of large area biomass estimates that are constrained by
4124 the limited spatial extent of forest inventories may be expanded through the use of
4125 remotely sensed data. Similarly, remotely sensed data can be used to fill spatial,
4126 attributional, and temporal gaps in forest inventory data, thereby augmenting and
4127 enhancing estimates of forest biomass and carbon stocks derived from forest inventory

4128 data. Such a hybrid approach is particularly relevant for non-merchantable forests where
4129 basic inventory data required for biomass estimation are lacking. Minimum mapping
4130 units are a function of the imagery upon which biomass estimates are made. Further,
4131 costs will be a function of the imagery desired, the areal coverage required, the
4132 sophistication of the processing, and needs for new plot data. For confidence in the
4133 outcomes of biomass estimation and mapping from remotely sensed data some form of
4134 ground calibration / validation data is required (Goetz et al., 2009).

4135

4136 Biomass estimates may range from local to global scales, and for some regions,
4137 particularly tropical forest regions, there are large variations in the estimates reported in
4138 the literature. Global and national estimates of forest above-ground biomass are often
4139 aspatial estimates, compiled through the tabular generalization of national level forest
4140 inventory data. Due to the importance for reporting and modeling, a wide-range of
4141 methods and data sources for generating spatially explicit large-area biomass estimates
4142 have been the subject of extensive research.

4143

4144 A variety of approaches and data sources have been used to estimate forest above
4145 ground biomass (AGB). Biomass estimation is typically generated from: (i) field
4146 measurement; (ii) remotely sensed data; or (iii) ancillary data used in GIS-based
4147 modeling. Estimation from field measurements may entail destructive sampling or direct
4148 measurement and the application of allometric equations. Allometric equations estimate
4149 biomass by regressing a measured sample of biomass against tree variables that are
4150 easy to measure in the field (e.g., diameter at breast height, height). Although equations
4151 may be species- or site-specific, they are often generalized to represent mixed forest
4152 conditions or large spatial areas. Biomass is commonly estimated by applying
4153 conversion factors (biomass expansion factors) to tree volume (either derived from field
4154 plot measures or forest inventory data). Relationships between biomass and other
4155 inventory attributes (e.g., basal area) have also been reported. The use of existing forest
4156 inventory data to map large area tree AGB has been explored; conversion tables were
4157 developed to estimate biomass from attributes contained in polygon-based forest
4158 inventory data, including species composition, crown density, and dominant tree height.

4159

4160 Remotely sensed data have become an important data source for biomass estimation.
4161 Generally, biomass is either estimated via a direct relationship between spectral
4162 response and biomass using multiple regression analysis, k-nearest neighbour, neural
4163 networks, statistical ensemble methods (e.g. decision trees), or through indirect
4164 relationships, whereby attributes estimated from the remotely sensed data, such as leaf
4165 area index (LAI), structure (crown closure and height) or shadow fraction are used in
4166 equations to estimate biomass. When using remotely sensed data for biomass
4167 estimation, the choice of method often depends on the required level of precision and
4168 the availability of plot data. Some methods, such as k-nearest neighbour require
4169 representative image-specific plot data, whereas other methods are more appropriate
4170 when scene-specific plot data are limited.

4171

4172 A variety of remotely sensed data sources continue to be employed for biomass mapping
4173 including coarse spatial resolution data such as SPOT-VEGETATION, AVHRR, and MODIS.
4174 To facilitate the linkage of detailed ground measurements to coarse spatial resolution
4175 remotely sensed data (e.g., MODIS, AVHRR, IRS-WiFS), several studies have integrated
4176 multi-scale imagery into their biomass estimation methodology and incorporated
4177 moderate spatial resolution imagery (e.g., Landsat, ASTER) as an intermediary data
4178 source between the field data and coarser imagery. Research has demonstrated that it is
4179 more effective to generate relationships between field measures and moderate spatial
4180 resolution remotely sensed data (e.g., Landsat), and then extrapolate these relationships
4181 over larger areas using comparable spectral properties from coarser spatial resolution

4182 imagery (e.g., MODIS). Following this approach alleviates the difficulty in linking field
4183 measures directly to coarser spatial resolution data, although a number of other
4184 techniques have been devised (see background readings).

4185

4186 Landsat TM and ETM+ data are the most widely used sources of remotely sensed
4187 imagery for forest biomass estimation. Numerous studies have generated stand
4188 attributes from LIDAR data, and then used these attributes as input for allometric
4189 biomass equations. Other studies have explored the integration of LIDAR and RADAR
4190 data for biomass estimation.

4191

4192 GIS-based modeling using ancillary data exclusively, such as climate normals,
4193 precipitation data, topography, and vegetation zones is another approach to biomass
4194 estimation. Some studies have also used geostatistical approaches (i.e., kriging) to
4195 generate spatially explicit maps of AGB from field plots, or to improve upon existing
4196 biomass estimation. More commonly, GIS is used as the mechanism for integrating
4197 multiple data sources for biomass estimation (e.g., forest inventory and remotely sensed
4198 data). For example, MODIS, JERS-1, QuickSCAT, SRTM, climate and vegetation data
4199 have been combined to model forest AGB in the Amazon Basin.

4200

4201 **2.7.5 Targeted airborne surveys to support carbon stock** 4202 **estimations – a case study**

4203

4204 Ground based methods for estimating biomass carbon of the tree component of forests
4205 are typically based on measurements of individual trees in many plots combined with
4206 allometric equations that relate biomass as a function of a single dimension, e.g.,
4207 diameter at breast height (dbh), or a combination of dimensions, such as dbh and
4208 height. A potential way of reducing costs of measuring and monitoring the carbon stocks
4209 of forests is to collect the key data remotely, particularly over large and often difficult
4210 terrain where the ability to implement an on-the-ground statistical sampling design can
4211 be difficult.

4212

4213 There are limitations of remotely sensed products to measure simultaneously the two
4214 key parameters for estimating forest biomass from above (i.e., tree height and tree
4215 crown area). However, positive experiences exist with systems using multispectral three-
4216 dimensional aerial digital imagery that usually fits on board a single-engine plane. Such
4217 systems collect high-resolution overlapping stereo images from a high-definition video
4218 camera (≤ 10 cm pixel size). Spacing camera exposures for 70–80 % overlap provides
4219 the stereo coverage of the ground while the profiling laser, inertial measurement unit,
4220 and GPS provide georeferencing information to compile the imagery bundle-adjusted
4221 blocks in a common three-dimensional space of geographic coordinates. The system also
4222 includes a profiling laser to record ground and canopy elevations. The imagery allows
4223 distinguishing individual trees, identifying their plant type and measuring their height
4224 and crown area. The measurements can be used to derive estimates of aboveground
4225 tree biomass carbon for a given class of individuals using allometric equations (e.g.
4226 between crown area and biomass). Biomass can be measured in the same way as in
4227 ground plots, to achieve potentially the same accuracy and precision, but with potentially
4228 less investment in resources. In addition, the data can be archived so that, if needed,
4229 the data could be re-evaluated or used for some future purpose.

4230

4231 As an example, the 3 D digital imagery system has been tested in highly heterogeneous
 4232 pine savanna (Brown et al, 2005) and a closed broadleaf forest (Pearson et al., 2005),
 4233 both in Belize. In the pine savanna, the extreme heterogeneity creates the requirement
 4234 for high intensity sampling and consequently very high on the ground measurement
 4235 costs. For the imagery system, the highest costs are fixed and the cost of analyzing high
 4236 numbers of plots is low in comparison to measurements on the ground (Brown et al.,
 4237 2005). The study of the closed tropical forest shows that its complex canopy is well
 4238 suited to the 3D imagery system. The complex multi-layered canopy facilitates the
 4239 identification and measurement of separate tree crowns. The studied area is particularly
 4240 suited due to its flat topography. In the closed forest it was often complex to measure
 4241 ground height adjacent to each tree, if topography were varied it would be necessary to
 4242 use an alternate equation that does not employ tree height and would therefore be less
 4243 precise.

4244

4245 **Table 2.7.3: Results from case studies using the 3D digital imagery system for**
 4246 **estimating carbon stocks of two forest types in Belize.**

Forest type	Number of imagery plots	Estimated carbon stock t C/ha	95% Confidence interval % of the mean	Reference
Closed tropical forest	39	117	7.4	Pearson et al. (2005)
Pine Savanna	77	13.1	16.8	Brown et al. (2005)

4247

4248 Imagery data are collected over the forest of interest by flying parallel transects. Once
 4249 the imagery are processed, individual 3D image pairs are systematically selected and
 4250 nested image plots (varying radii to account for the distribution of small to large crowned
 4251 trees) are placed on the imagery and trees crown and height measurements taken
 4252 (system uses ERDAS and Stereo Analyst). To convert the measurements from the
 4253 imagery to estimates of biomass carbon, a series of allometric equations between tree or
 4254 shrub biomass carbon were developed. The allometric equations resulting from this
 4255 analysis were applied to crown area and vegetation height data obtained from the
 4256 analysis of the imagery to estimate biomass carbon per plot and then extrapolated to
 4257 per-hectare values (Table 2.7.3).

4258

4259 In terms of cost, an airplane, with aviation gas and pilot is needed to collect the
 4260 imagery; experience has shown this to cost approximately US\$ 300 per hour of engine
 4261 time. Using a conventional field approach, the equivalent cost would be a vehicle rental
 4262 for 20-50 day, the cost of which depends on local country conditions. . In the Belize
 4263 pine savanna study, it was found that the break-even point in person-hours was at 25
 4264 plots, where the conventional field approach was more time-efficient. However, as more
 4265 than 200 plots would be needed in the pine savanna to achieve precision levels of less
 4266 than 10% of the mean, the targeted airborne approach clearly has an advantage, even
 4267 considering the different skill set needed by each approach. For the closed forest, just 39
 4268 plots were needed to estimate biomass carbon with 95 % confidence intervals equal to
 4269 7.4 % of the mean compared to the 101 ground plots that produced a comparable
 4270 estimate with confidence intervals equal to 8.5 % of the mean.

4271

4272 **2.7.6 Modeling and forecasting forest-cover change**

4273

4274 Most models of forest-cover change at the landscape to the national scales address one
4275 of the following questions (sometimes they deal with the two at once): (i) Which
4276 locations are most likely to be affected by forest-cover change in the near future? (ii) At
4277 what rate are forest-cover changes likely to proceed in a given region?

4278

4279 Predicting the location of future forest-cover change is a rather easy task, provided that
4280 current and future processes of forest-cover change are similar to those that operated in
4281 the recent past. Statistical relationships are calibrated between landscape determinants
4282 of land-use changes (e.g., distance to roads, soil type, market accessibility, terrain) and
4283 recently observed spatial patterns of forest-cover change. The analysis of spatially-
4284 explicit deforestation maps, i.e. generated to estimate activity data for IPCC reporting,
4285 can provide a suitable database for such analysis. Both the shape and pattern of the
4286 deforestation observed (location, size, fragmentation), as well as, their relationship with
4287 spatial factors influencing forest change can be quantified and empirical relationship
4288 established. Such understanding can drive spatially-explicit statistical models are then
4289 used to produce a "suitability map" for a given type of forest-cover change. Such models
4290 are born from the combination of geographic information systems (GIS) and multivariate
4291 statistical models. Their goal is the projection and display, in a cartographic form, of
4292 future land use patterns which would result from the continuation of current land uses.
4293 Note that regression models cannot be used for wide ranging extrapolations in space and
4294 time.

4295

4296 Predicting future rates of forest-cover changes is a much more difficult task. Actually,
4297 the quantity of deforestation, forest degradation, or reforestation in a given location
4298 depends on underlying driving causes. These indirect and often remote causes of forest-
4299 cover change are generally related to national policies, global markets, human
4300 migrations from other regions, changes in property-right regimes, international trade,
4301 governance, etc. The relative importance of these causes varies widely in space and
4302 time. Opportunities and constraints for new land uses, to which local land managers may
4303 respond by changing forest cover, are created by markets and policies that are
4304 increasingly influenced by global factors (Lambin et al., 2001). Extreme biophysical
4305 events occasionally trigger further changes. The dependency of causes of land-use
4306 changes on historical, geographic and other factors makes it a particularly complex issue
4307 to model. Transition probability models, such as Markov chains, project the amount of
4308 land covered by various land use types based on a sample of transitions occurring during
4309 a previous time interval. Such simple models rely on the assumption of the stationarity
4310 of the transition matrix - i.e. temporal homogeneity. The stochastic nature of Markov
4311 chain masks the causative variables.

4312

4313 Many economic models of land-use change apply optimisation techniques based either
4314 on whole-farm analyses at the microeconomic level (using linear programming) or
4315 general equilibrium models at the macroeconomic scale (Kaimowitz and Angelsen,
4316 1998). Any parcel of land, given its attributes and its location, is modelled as being used
4317 in the way that yields the highest rent. Such models allow investigation of the influence
4318 of various policy measures on land allocation choices. The applicability of micro-
4319 economic models for projections is however limited due to unpredictable fluctuations of
4320 prices and demand factors, and to the role of non-economic factors driving forest-cover
4321 changes (e.g., corruption practices and low timber prices that underlie illegal logging).

4322

4323 Dynamic simulation models condense and aggregate complex ecosystems into a small
4324 number of differential equations or rules in a stylised manner. Simulation models are
4325 therefore based on an a priori understanding of the forces driving forest-cover change.
4326 The strength of a simulation model depends on whether the major features affecting
4327 land-use changes are integrated, whether the functional relationships between factors
4328 affecting change processes are appropriately represented, and on the capacity of the
4329 model to predict the most important ecological and economic impacts of land-use
4330 changes. Simulation models allow rapid exploration of probable effects of the
4331 continuation of current land use practices or of changes in cultural or ecological
4332 parameters. These models allow testing scenarios on future land-use changes. When
4333 dynamic ecosystem simulation models are spatially-explicit (i.e., include the spatial
4334 heterogeneity of landscapes), they can predict temporal changes in spatial patterns of
4335 forest use.

4336

4337 Agent-based models simulate decisions by and competition between multiple actors and
4338 land managers. In these behavioural models of land use, decisions by agents are made
4339 spatially-explicit thanks to cellular automata techniques. A few spatially-explicit agent-
4340 based models of forest-cover change have been developed to date. These grid-cell
4341 models combine ecological information with socio-economic factors related to land-use
4342 decisions by farmers. Dynamic landscape simulation models are not predictive systems
4343 but rather "game-playing tools" designed to understand the possible impacts of changes
4344 in land use. Dynamic landscape simulation models are specific to narrow geographic
4345 situations and cannot be easily generalised over large regions.

4346

4347 All model designs involve a great deal of simplification. While, by definition, any model
4348 falls short of incorporating all aspects of reality, it provides valuable information on the
4349 system's behaviour under a range of conditions (Veldkamp and Lambin, 2001). Current
4350 models of forest-cover change are rarely based on processes at multiple spatial and
4351 temporal scales. Moreover, many land use patterns have developed in the context of
4352 long term instability (e.g., fluctuations in climate, prices, state policies). Forest-cover
4353 change models should therefore be built on the assumption of temporal heterogeneity
4354 rather than on the common assumption of progressive, linear trends. Rapidly and
4355 unpredictably changing variables (e.g., technological innovations, conflicts, new policies)
4356 are as important in shaping land use dynamics as the slowly and cumulatively changing
4357 variables (e.g., population growth, increase in road network).

4358

4359 **2.7.7 Summary and recommendations**

4360 The techniques and approaches outlined in previous sections are among the most
4361 important ones with the potential to improve national monitoring and assessing carbon
4362 emissions from deforestation and forest degradation for REDD implementation. Their
4363 usefulness should be judged by a number factors including:

- 4364 • Data characteristics & spatial/temporal resolution of current observations/sensors
- 4365 • Operational calibration and interpretation/analysis methods
- 4366 • Area of contribution to existing IPCC land sector reporting and sourcebook
4367 approach
- 4368 • Estimated monitoring cost (i.e. per km²)
- 4369 • Experiences for monitoring purposes, i.e. examples for large scale or national
4370 demonstration projects
- 4371 • Data availability, coverage and access procedures
- 4372 • Known limitations and challenges, and approaches to deal with them

- 4373
- National capacities required for operational implementation
- 4374
- Status, expected near-term developments and long-term sustainability

4375

4376 There is a clear role for the international community to assist countries and actors
4377 involved in REDD monitoring in the understanding, usefulness and progress of evolving
4378 technologies. This involves a proper communication on the activities needed and actions
4379 taken to evaluate and prototype REDD monitoring using data and techniques becoming
4380 increasingly available. Near-term progress is particularly expected in the availability and
4381 access to suitable remote sensing datasets. Currently Landsat data are the most
4382 common satellite dataset for forest monitoring on the national level. Several factors are
4383 responsible for this including rigorous geometric and radiometric standards, the image
4384 characteristics most known and useful for large area land cover mapping and dynamics
4385 studies, and the user-friendly data access policy. Thus, there are important differences in
4386 the usefulness of existing data sources depending on the following characteristics:

- 4387
- I. Observations are being continuously acquired and datasets archived by national
4388 or international agencies;
 - 4389 II. There is general understanding on the availability (i.e., global cloud-free
4390 coverage), quality and accessibility of the archived data;
 - 4391 III. Data are being pre-processed (i.e. geometrically and radiometrically corrected)
4392 and are made accessible to the monitoring community;
 - 4393 IV. Pre-processed datasets are available in international or national mapping
4394 agencies for land cover and change interpretation;
 - 4395 V. Sustained capacities exist to produce and use land cover datasets within
4396 countries and for global assessments (e.g., in developing countries).

4397

4398 Existing and archived satellite data sources are not yet fully explored for forest
4399 monitoring. Ideally, all relevant observations (satellite and in situ) should meet a set of
4400 six requirements in Table 2.7.4 to be considered fully useful and operational. Table 2.7.4
4401 further emphasizes that active satellite remote sensing data (i.e. Radar and Lidar) are
4402 becoming more available on a continuous basis and suitable for change analysis. This will
4403 enable better synergistic use with current optical sensors, to increase frequency of cloud
4404 free data coverage and enhance the detailed and accuracy of monitoring products.

4405

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Table 2.7.4: Current availability of fine-scale satellite data sources and capacities for global land cover change observations given six general requirements (Note: dark gray=common or fully applicable, light gray=partially applicable/several examples, white=rare or no applications or examples).

	Satellite observation system/program	Technical observation challenges solved	Access to information on quality of archived data worldwide	Continuous observation program for global coverage	Pre-processed global image datasets generated & accessible	Image data available in mapping agencies for land change analysis	Capacities to sustainably produce/ use map products in developing countries
O	LANDSAT TM/ETM						
P	ASTER				On demand		
T	SPOT HRV (1-5)				Commercially		
I	CBERS 1-3				Regionally		
C	IRS / Indian program				Regionally		
A	DMC program			Probably	Commercially		
L	ALOS/PALSAR + JERS				Regionally		
S	ENVISAT ASAR, ERS 1+2				Regionally		
A	TERRARSAR-X				Commercially		
R	IKONOS, GEOEye			Probably	Commercially		
	ICESAT/GLAS (LIDAR)						

4410

4411

4412 The international Earth observation community is aware of the needs for pre-processed
4413 satellite data being available in developing countries. The gap between acquiring satellite
4414 observations and their availability (in the archives) and processing the data in a suitable
4415 format to be ready for use by developing countries for their forest area change
4416 assessments is being bridged the space agencies and data providers such as USGS,
4417 NASA, ESA, JAXA, INPE, and international coordination mechanism of CEOS, GOF-C-GOLD
4418 and GEO. These efforts will in the next few years further decrease the amount of costs
4419 and efforts to use satellite observations for national-level REDD monitoring.

4420

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4472

4473 **3 PRACTICAL EXAMPLES FOR DATA COLLECTION**

4474

4475 **3.1 OVERVIEW OF METHODS USED BY ANNEX-1** 4476 **COUNTRIES FOR NATIONAL LULUCF INVENTORIES**

4477 Giacomo Grassi, Joint Research Centre, Italy

4478 Michael Brady, Natural Resources Canada - Canadian Forest Service

4479 Stephen Kull, Natural Resources Canada - Canadian Forest Service

4480 Werner Kurz, Natural Resources Canada - Canadian Forest Service

4481 Gary Richards, Department of Climate Change, Australia

4482

4483 **3.1.1 Scope of chapter**

4484 Given the high heterogeneity that characterizes the landscape of most Annex-1
4485 countries, the estimation of GHG emissions and removals from the Land Use, Land Use
4486 Change and Forestry (LULUCF) sector typically represents one of the most challenging
4487 aspects of the national GHG inventories. This is witnessed also by the fact that, based on
4488 the information submitted annually to UNFCCC⁵¹, it emerges that the LULUCF sector of
4489 most Annex-1 countries is still not fully complete (in terms of categories and carbon
4490 pools), and that uncertainties are still rather high. However, it should be also considered
4491 that, given the imminent reporting under the Kyoto Protocol (from 2010), significant
4492 improvements will likely occur in coming years.

4493 This heterogeneity is also reflected in the methods used by Annex-1 countries to
4494 estimate GHG emissions and removals from the LULUCF sector, which largely depend on
4495 national circumstances, including available data and their characteristics.

4496 With regard to the category "forest land", in most Annex-1 countries, forest inventories
4497 provide the basic inputs for both activity data (area of forest and conversions to/from
4498 forest) and emission factors (carbon stock changes in the various pools). Furthermore,
4499 the use of satellite data is not yet very common for LULUCF inventories, although the
4500 situation may rapidly change. Exceptions already exist, with some countries without
4501 forest inventories relying heavily on satellite data and modelling approaches.

4502 This section provides a short overview of the variety of methods used by Annex-1
4503 countries for estimating forest area changes (3.1.2), carbon stock changes (3.1.3) and
4504 the related uncertainties (3.1.4). It also includes two relevant examples illustrating how
4505 empirical yield-data driven modeling (Canada) and process modeling (Australia) can be
4506 used to estimate GHG emissions and removals from LULUCF.

4507

⁵¹ National inventory reports by Annex-1 countries can be found at:
http://unfccc.int/national_reports/annex_i_ghg_inventories/items/2715.php

4508 **3.1.2 Methods for estimating forest area changes**

4509 The identification of the activity data (area of a land use category, e.g. forest land) often
4510 represents the most difficult step for a LULUCF GHG inventory. This is witnessed, for
4511 example, by the fact that significant time-series inconsistencies (e.g. when the sum of all
4512 land use areas oscillates over time) are relatively frequent in Annex-1 LULUCF
4513 inventories. In particular, the main challenge is represented by areas subject to land use
4514 changes (e.g. to/from forest): about 30% of Annex-1 countries do not report yet "land
4515 converted to forest" (i.e. which is often included in the category "forest remaining
4516 forest") and about 50% do not report yet deforestation (despite in some cases the
4517 deforested area is likely to be non-negligible). Although the situation will certainly
4518 improve when the reporting under the Kyoto Protocol will start in 2010, the current
4519 situation demonstrates the difficulty of representing land use areas and area changes,
4520 especially in the very fragmented landscapes which characterize most of Annex-1
4521 countries.

4522 Depending on the available data, various methodologies are applied by Annex I countries
4523 to generate the time series for annual activity data. In any case, as most of the
4524 methodologies are not capable to generate data with annual time steps, interpolation
4525 and extrapolation techniques (i.e., between years or beyond the latest available year)
4526 are widely used produce the annual data needed for a GHG inventory.

4527 Given the predominant role that remote sensing will likely play in the future REDD
4528 implementation, here we mainly focus on this methodology.

4529 According to the information available from the latest National Inventory Reports (NIR)
4530 (Table 3.1, from Achard et al. 2008), only 23 Annex-1 countries (about 60%) explicitly
4531 indicated the use of some remote sensing techniques (or the use of related products,
4532 e.g. Corine Land Cover) in the preparation of their GHG inventories. Generally, these
4533 countries integrated the existing ground-based information (e.g., national statistics for
4534 the agricultural, forestry, hydraulic and urban sectors, vegetation and topographic maps,
4535 climate data) with remote sensing data (like aerial photographs, satellite imagery using
4536 visible and/or near-infrared bands, etc.), using GIS techniques.

4537 In particular, the following remote sensing techniques were used:

4538 1) Aerial photography: although analysis of aerial photographs is considered one of the
4539 most expensive method for representing land areas, 11 Annex-1 countries used this
4540 methodology, in combination with ground data and in some case with other
4541 techniques or land cover map (e.g. CORINE Land cover), to detect land use and land
4542 use changes. For instance, France used 15600 aerial photographs together with
4543 ground surveys (TerUti LUCAS). The reason is essentially due to the existence for
4544 some countries of historic aerial photos acquired for other purposes; although these
4545 images are sometimes characterized by different spatial resolution and quality, they
4546 permit to monitor accurately land use and land use changes back in the past.

4547 2) Satellite imagery (using visible and/or near-infrared bands and related products):
4548 only very few countries used detailed satellite imagery in the visible and/or near-
4549 infrared bands for representing land areas.

4550 For example, Australia combined coarse (NOAA/AVHRR) and detailed (LANDSAT
4551 MMS, TM, ETM+) satellite imagery to obtain long time series of data (see Ch. 3.1.4.1
4552 for further details). Canada uses satellite imagery to generate a detailed mosaic of
4553 distinct land cover categories; according to their NIR, in 2006 they used LANDSAT,
4554 SPOT, IRS (Indian Remote Sensing System) imagery and Google maps (based on
4555 LANDSAT and QUICKBIRD) whereas in 2007 only LANDSAT imagery were used.

4556 New Zealand based their Land Cover Database (LCDB1 and 2) on SPOT (2 and 3)
4557 and LANDSAT 7 ETM+ satellite imagery; mapping of land use in 2009 will use SPOT 5
4558 satellite imagery. Within the LUCAS project (Land Use and Carbon Analysis System),
4559 the location and timing of forest harvesting will be identified with medium spatial
4560 resolution (250 m) MODIS satellite imagery, while the actual area of harvesting and

4561 deforestation will be determined with high resolution satellite systems or aerial
4562 photography.

4563 France used numerous satellite images for representing land areas of French
4564 Guyana: in total, 16786 ground points were analyzed in 1990 and 2006 using
4565 LANDSAT and SPOT imagery, respectively.

4566 **Table 3.1: Use of Remote Sensing in Annex I Countries, as reported in their**
4567 **latest National Inventory Reports (from Achard et al. 2008).**

Annex-I Countries	Aerial Photography	Satellite imagery (using visible and/or near-infrared bands and related products)				Satellite or airborne radar imagery	Airborne LIDAR
		Coarse resolution	Medium resolution	Fine resolution	CORINE (CLC)		
Australia	Yes	Yes	Yes				
Austria							
Belgium					Yes ⁴		
Bulgaria							
Canada	Yes		Yes	Yes ²			
Croatia							
Czech Republic					Yes		
Denmark							
Estonia					Yes ⁴		
Finland		Yes ^{5,6}					
France	Yes		Yes ⁵				
Germany					Yes ⁴		
Greece							
Hungary					Yes ⁴		
Iceland			Yes		Yes ¹		
Ireland					Yes		
Italy	Yes		Yes ¹		Yes ⁴		
Japan	Yes ⁴						
Latvia							
Liechtenstein	Yes						
Lithuania							
Luxembourg	Yes		Yes ¹				
Monaco							
Netherlands			Yes ¹				
New Zealand	Yes	Yes ¹	Yes	Yes ¹		Yes ¹	Yes ¹
Norway	Yes						Yes ³
Poland							
Portugal					Yes ⁴		
Romania							
Slovakia							
Slovenia							
Spain					Yes ⁴		
Sweden		Yes ^{4,5,6}					
Switzerland	Yes						
Turkey					Yes ⁴		
Ukraine							
United Kingdom							
USA	Yes		Yes ⁶				

4568
4569 Notes: 1. Use of this methodology planned in the future; 2. Methodology reported in previous NIR but not in
4570 the latest; 3. The intention to use this methodology reported in previous NIR but not in the latest; 4.
4571 Methodology used only for reporting of some IPCC categories; 5. Methodology used only for reporting of a
4572 portion of territory of the Country; 6. Methodology not specified. Note that NIRs by Russian Federation and
4573 Belarus were not included in this analysis because only available in Russian.

4574

4575 Some European countries reported the use of satellite imagery for supporting
4576 stratification of the national forest inventory. Furthermore, 10 countries used existing
4577 land cover maps, like the CORINE products (1990 and or 2000 maps, and the
4578 associated change product), that are based on interpretation of satellite imagery and
4579 their verification through ground surveys. For example, Czech Republic and Ireland
4580 used the CORINE products for reporting all the categories indicated by IPCC (2003),
4581 whereas other countries used the CORINE Land Cover map (CLC) to report only some
4582 IPCC categories, like Estonia (organic soils), Hungary (wetlands), Germany, Italy,
4583 Portugal, Spain and Turkey.

4584 3) Satellite or airborne radar imagery: none countries reported the use of satellite or
4585 airborne radar imagery for representing land areas. New Zealand may use satellite
4586 radar, within the LUCAS project, to identify the location and timing of forest
4587 harvesting if the evaluation of using medium spatial resolution (250 m) MODIS
4588 satellite images will be unsuccessful.

4589 4) Airborne LIDAR (Light Detecting and Ranging): only New Zealand reports the use of
4590 airborne LiDAR, in combination with field measurements, to estimate for 2008 the
4591 changes in carbon stocks in forests planted after January 1st 1990, within plots
4592 established on a 4 km grid across the country. The LiDAR data are calibrated against
4593 the field measurements and only for forest plots that are inaccessible LiDAR data will
4594 be processed to provide the total amount of carbon per plot; the measurement
4595 process on the same plots will be repeated at the end of the Kyoto Protocol's
4596 commitment period (around 2012).

4597 In conclusion, only a minority of countries – typically characterized by large land areas
4598 not easily accessible - makes a direct use of satellite-remote sensing for GHG inventory
4599 preparation. By contrast, most European countries - typically characterized by a more
4600 intensive land management and by a long tradition of forest inventories – do not use
4601 satellite-remote sensing or uses only derived products such as CORINE, at least for
4602 gathering ancillary information. In these cases, forest area and forest area changes are
4603 determined through other methods, including permanent plots, forest and agricultural
4604 surveys, census, registries or observational maps.

4605 Thus, in most cases, the use of satellite data for LULUCF inventories by Annex-1
4606 countries is currently not as important as it will likely be for REDD. However, the
4607 situation seems in rapid development, as several Annex I countries have indicated the
4608 intention to use more remote sensing data in the near future (e.g., Italy, Netherlands,
4609 Denmark, Luxembourg, Iceland). Furthermore, the fact that the stringent reporting
4610 under Kyoto Protocol is approaching means that several countries are struggling in
4611 improving GHG inventories, which may involve a more intensive use of remote sensing
4612 products.

4613

4614 **3.1.3 Methods for estimating carbon stock changes**

4615 As explained in Chapter 2.4, the approaches used to assess the changes of carbon stocks
4616 in the the different carbon pools are essentially two: the "gain-loss" approach
4617 (sometimes called "process-based" or "IPCC default"), which estimates the net balance
4618 of additions to and removals from a carbon pool, and the "stock change" (or "stock-
4619 difference"), which estimates the difference in carbon stocks in a given carbon pool at
4620 two points in time. While the gain-loss can be applied with all tier levels, the stock
4621 change approach typically requires country-specific information (i.e. at least tier 2).

4622 In general, for the category "forest land", the most important pool in terms of carbon
4623 stock changes is the aboveground biomass, both for the removals (e.g. in "land
4624 converted to forest" and "forest remaining forest") and for the emissions (e.g.
4625 deforestation); however, some exception may also occur, e.g. emissions from organic
4626 soils may be far more relevant than carbon stock changes in biomass.

4627 For the aboveground biomass pool of forest, the majority of Annex-1 countries either use
4628 the gain-loss or a mix of the two approaches, depending on the availability of data; in
4629 this case, tier 2 or tier 3 methods are typically applied, i.e. the input for calculating
4630 carbon stock changes are country-specific data on growth, harvest and natural
4631 disturbances (e.g. forest fires), often based on or complemented by yield models (e.g.
4632 UK, Italy, Ireland). By contrast, relatively few countries indicate the use of the stock
4633 change approach (e.g. Sweden, Germany, Spain, Belgium, US). Both approaches use
4634 (directly or indirectly) of timber volume data collected through regional or national forest
4635 inventories; in these cases, the conversion from timber volume into carbon stock is
4636 generally done with country-specific biomass functions (e.g. Austria, Finland, Ireland and
4637 Spain) or biomass expansion factors. For belowground biomass, most countries use
4638 default or country-specific ratios of above to belowground biomass.

4639 Regarding the other pools (dead organic matter and soils) the situation is rather diverse.
4640 In several cases, due to the lack of appropriate data, the tier-1 method is used, which
4641 assumes no change in carbon stock (except for drained organic soils) in case of no
4642 change in land uses (e.g. forest remaining forest). For dead organic matter and soils this
4643 assumption is applied by about 50% and 70% of Annex-1 countries, respectively; the
4644 other countries use either country-specific factors or models (i.e. tier 2 and 3 methods).
4645 In case of land use change (from/to forest), the carbon stock changes of these pools is
4646 generally assessed by the difference of carbon stock reference values (in most cases
4647 country-specific and appropriately disaggregated) between the two land uses.

4648

4649 **3.1.4 National carbon budget models**

4650 This chapter illustrates two relevant examples of tier-3 models for estimating GHG
4651 emissions and removals from forests: an empirical yield-data driven model (Canada,
4652 3.1.4.1) and a satellite data-driven process model (Australia, 3.1.4.2).

4653

4654 **3.1.4.1 The Operational-Scale Carbon Budget Model of the Canadian Forest** 4655 **Sector (CBM-CFS3)**

4656 For over two decades, Natural Resources Canada's Canadian Forest Service (CFS) has
4657 been involved in research aimed at understanding and modeling carbon dynamics in
4658 Canada's forest ecosystems. In 2001, the CFS in partnership with Canada's Model
4659 Forest Network set out to design, develop and distribute an operational-scale forest
4660 carbon accounting modeling software program to Canada's forestry community. The
4661 software would give forest managers, be they small woodlot owners or provincial or
4662 industrial forest managers, a tool with which to assess their forest ecosystem carbon
4663 stocks, and forest management planning options in terms of their ability to sequester
4664 and store carbon from the atmosphere.

4665 The CBM-CFS3 was also developed to be the central model of Canada's National Forest
4666 Carbon Monitoring, Accounting and Reporting System (NFCMARS) (Kurz and Apps 2006),
4667 which is used for international reporting of the carbon balance of Canada's managed
4668 forest (Kurz et al. 2009). Its purpose is to estimate forest carbon stocks, changes in
4669 carbon stocks, and emissions of non-CO₂ greenhouse gases in Canada's managed
4670 forests. The NFCMARS is based on an empirical yield-data driven model approach. It is
4671 designed to estimate past changes in forest carbon stocks—i.e., from 1990 to 2007
4672 (monitoring)—and to predict, based on scenarios of future disturbance rates, land-use
4673 change and management actions, changes in carbon stocks in the next two to three
4674 decades (projection).

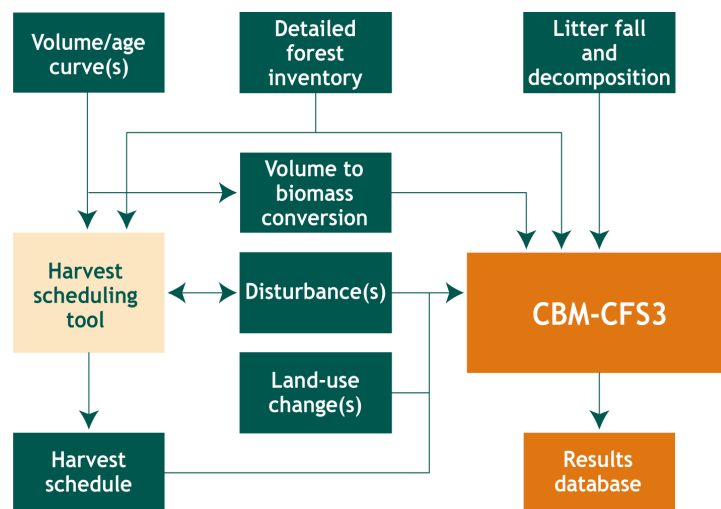
4675 The system integrates information - such as forest inventories, information on forest
4676 growth and yield obtained from temporary and permanent sample plots, statistics on
4677 natural disturbances such fires and insects, and land-use change and forest management

4678 activities. The NFCMARS modeling framework incorporates the best available information
 4679 and scientific understanding of the ecological processes involved in forest carbon cycling
 4680 (Figure 3.1.1). Key elements of the System include:

- 4681 • **The Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3)**
- 4682 • **Tracking Land-Use Change** (monitoring changes in carbon stocks that
 4683 result from afforestation, reforestation, or deforestation activities in Canada)
- 4684 • **Forest Inventory** (area-based inventory approach for managed and
 4685 unmanaged forest)
- 4686 • **Forest Management and Disturbance Monitoring** (use the best available
 4687 statistics on forest management and natural disturbances, obtained from the
 4688 National Forestry Database program, the Canadian Wildland Fire Information
 4689 System, and from provincial and territorial resource management agencies)
- 4690 • **Spatial Framework** (A nested ecological framework, consisting of 18
 4691 reporting zones based on the Terrestrial Ecozones of Canada. Beneath these,
 4692 2 layers of nested spatial units comprised of 60 reconciliation units and over
 4693 500 management units are included.)
- 4694 • **Special Projects** to advance the scientific basis of the NFCMARS, a number
 4695 of special research, monitoring and modeling projects are conducted (Fluxnet
 4696 studies, adding spatially explicit modeling, dead organic matter calibration and
 4697 uncertainty and sensitivity analysis)
- 4698 •

4699 **Figure 3.1.1: CBM-CFS3 uses data from forest management planning for**
 4700 **national-scale integration of forest C cycle data.**

4701



4702

4703

4704 Main outputs:

- 4705 • **National Inventory Report** (as every Annex-1 country, Canada prepares an
 4706 annual National Inventory Report detailing the country's greenhouse gas
 4707 emissions and removals, as per United Nations Framework Convention on Climate
 4708 Change guidelines (UNFCCC) http://www.ec.gc.ca/pdb/ghg/inventory_e.cfm).
- 4709 • **Policy Development Support** (work with policy makers in both the federal and
 4710 provincial governments to ensure forest policy development is supported by
 4711 sound science)

4712 The CBM-CFS3 is a stand- and landscape level modeling framework that simulates the
 4713 dynamics of all forest carbon stocks required under the UNFCCC. It is compliant with the

4714 carbon estimation methods of the Tier-3 approach outlined in the Good Practice
4715 Guidance for Land Use, Land-Use Change, and Forestry (2003) report published by the
4716 Intergovernmental Panel on Climate Change (IPCC 2003).

4717 The model builds on the same information used for forest management planning
4718 activities (e.g., forest inventory data, tree species, natural and human-induced
4719 disturbance information, forest harvest schedules and land-use change information),
4720 supplemented with information from national ecological parameter sets and volume-to-
4721 biomass equations appropriate for Canadian species and forest regions.

4722 Although the model currently contains a set of default ecological parameters appropriate
4723 for Canada, these parameters can be modified by the user, allowing for the potential
4724 application of the model in other countries. Other languages are being added to the user
4725 interface.

4726 **International activities**

4727 The CFS Carbon Accounting Team (CAT) holds CBM-CFS3 training workshops across
4728 Canada. Many foreign participants have also been trained. Interest in Canada's
4729 innovative approach to forest GHG modeling and reporting through the NFCMARS has
4730 been growing. In 2005, NRCAN began a bilateral project with the Russian Federal Forest
4731 Agency to share knowledge and approaches to forest carbon accounting with scientists in
4732 Russia where the model has been used for regional- and national-scale analyses. More
4733 recently, the CFS-CAT began a collaborative project with CONAFOR (Comisión Nacional
4734 Forestal), the Government of Mexico's Ministry of Forests, to assess and test the
4735 suitability of the CBM-CFS3 in the wide range of forests and climates of that country. The
4736 aim of the project is to determine whether the model could contribute towards Mexico's
4737 GHG accounting system and towards Mexico's efforts to account for the effects of
4738 reducing emissions from deforestation and degradation (REDD). The model can be used
4739 in REDD or project-based mitigation efforts to provide both the baseline and the with-
4740 project estimates of GHG emissions and removals.

4741 The CFS-CAT is continuing to develop and refine the CBM-CFS3 to accommodate
4742 improvements in the science of the forest carbon cycle, changes in policy surrounding
4743 climate change and forests, and changes to broaden the use and applicability of the
4744 model in other ecosystems. For more information visit: <http://carbon.cfs.nrcan.gc.ca>

4745

4746 **3.1.4.2 National Carbon Accounting System (NCAS) of Australia**

4747 The NCAS was established by the Australian Government in 1998 to comprehensively
4748 monitor greenhouse gas emissions at all scales (project through to national), with
4749 coverage of all pools (living biomass, debris and soil), all gases (CO₂ and non-CO₂), all
4750 lands and all activities. The approach is spatially and temporally explicit, and inclusive of
4751 all lands and causes of emissions and removals, including climate variability. It is
4752 currently the only example of the full application of a Tier 3, Approach 3 modeling
4753 system.

4754 The NCAS represents one of the few examples of a fully integrated, purpose built carbon
4755 accounting system that is not based around a long-term national forest inventory (which
4756 did not exist in Australia). The system was designed specifically to meet Australia's
4757 international reporting needs (UNFCCC and Kyoto) as well as supporting project based
4758 accounting under future market mechanisms. The key policy issues that the system was
4759 designed to address were:

- 4760 • Nationally consistent reporting for all lands
- 4761 • Reporting of emissions and removals for 1990
- 4762 • Sub hectare reporting as required by the Kyoto protocol
- 4763 • Geographic identification of projects

4764

4765 A key issue faced by Australia in developing the NCAS was the lack of complete and
4766 consistent national forest inventory information, especially in the woodland forests where
4767 the majority of Australia's land use change occurs. Implementing a national forest
4768 inventory was considered as an option, but was rejected as it would have been
4769 extremely costly to establish and maintain, would not have provided the information
4770 required to develop an accurate estimate of emissions and removals in 1990 and would
4771 not have been able to include all pools and all gases. Instead, Australia developed an
4772 innovative system utilizing a variety of ground measured and remotely acquired data
4773 sources integrated with ecosystem models to allow for fully spatial explicit modeling. The
4774 key elements of the system are:

- 4775 • The Full Carbon Accounting Model (FullCAM)
- 4776 • Time series consistent, complete wall-to-wall mapping of forest extent and
4777 change in forest extent from 1972 at fine spatial scales (25 m pixel) using
4778 Landsat data
- 4779 • Spatially and temporally explicit climate data (e.g. rainfall, vapour pressure
4780 deficit, temperature) and spatially explicit biophysical data (e.g. soil types, carbon
4781 contents)
- 4782 • Species and management information
- 4783 • Extensive model calibration and validation ground data

4784

4785 The core component of the NCAS is the Full Carbon Accounting Model (FullCAM). FullCAM
4786 is best described as a mass balance, C:N ratio, hybrid process-empirical ecosystem
4787 model that calculates carbon and nitrogen flows associated with all biomass, litter and
4788 soil pools in forest and agricultural systems. FullCAM uses a variety of spatial and
4789 temporal data, tabular and remotely sensed data to allow for the spatially explicit
4790 modeling of:

- 4791 • Forests, including the effects of thinnings, multiple rotations and fires
- 4792 • Agricultural cropping or grazing systems - including the effects of harvest,
4793 ploughing, fire, herbicides and grazing
- 4794 • Transitions between forest and agriculture (afforestation, reforestation and
4795 deforestation)

4796 The hybrid approach applied in FullCAM uses process models to describe relative site
4797 productivity and the effects of climate on growth and decay, while simple empirical
4798 models set the limits and general patterns of growth. Hybrid approaches have the
4799 advantage of being firmly grounded by empirical data while still reflecting site conditions.
4800 The seamless integration of the component models in a mass-balance framework allows
4801 for the use field-based techniques to directly calibrate and validate estimates. These
4802 data have been obtained from a variety of sources including:

- 4803 • A thorough review of existing data in both the published and unpublished (e.g.
4804 PhD theses) literature including biomass, debris and soil carbon
- 4805 • A comprehensive soil carbon sampling system to validate model results
- 4806 • Full destructive sampling of forests to obtain accurate biomass measurements
- 4807 • Analysis of existing research data for site specific model calibration and testing
- 4808 • Ongoing research programs on soil carbon, biomass and non-CO2 emissions

4809

4810 FullCAM, the related data and the NCAS technical report series are freely available as
4811 part of the National Carbon Accounting Toolbox
4812 (<http://www.climatechange.gov.au/ncas/ncat/index.html>). The Toolbox allows users to

4813 develop project level accounts for their property using the tools and data used to
4814 develop the national accounts.

4815

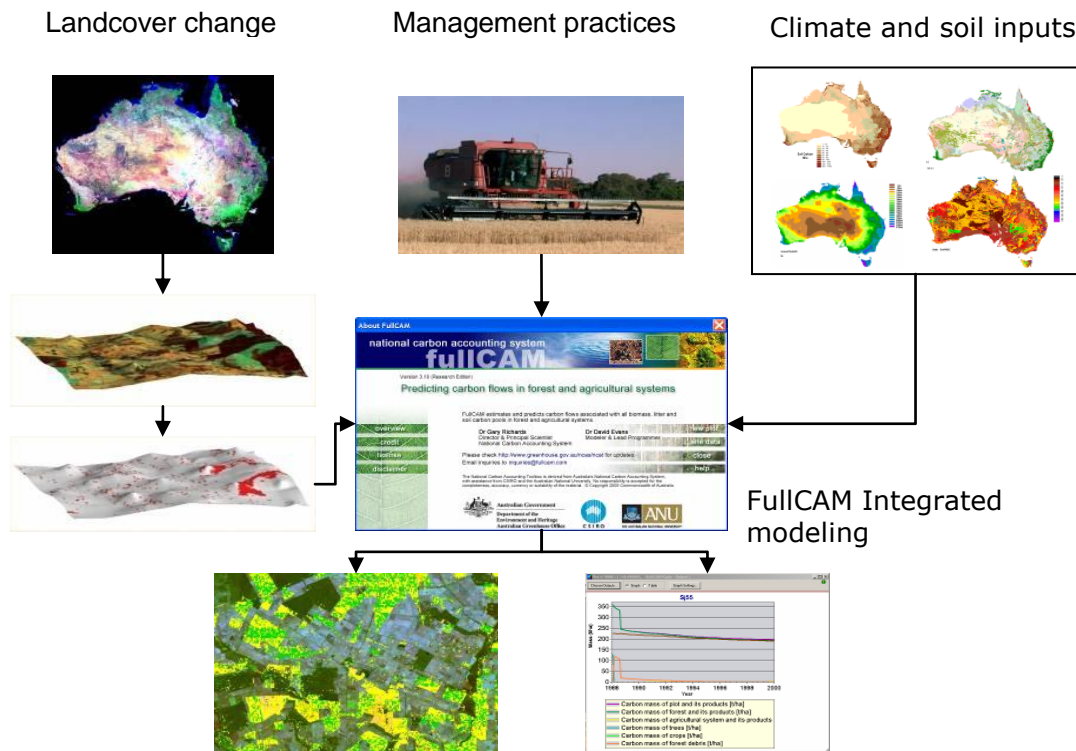


Figure 3.1.2: Graphical depiction of the NCAS modeling framework

4816

4817 International activities

4818 Australia has developed considerable experience and expertise in developing carbon
4819 accounting systems to monitor land use change over the past decade. Australia is
4820 currently involved directly with countries such as Indonesia and Papua New Guinea and
4821 indirectly through the Clinton Climate Initiative to pass on the experiences of developing
4822 the NCAS. Rather than promoting the direct application of the Australian NCAS modeling
4823 system, the Australian Government is providing policy and technical advice to allow
4824 countries to design and develop their own systems to meet their own specific conditions.
4825 Like the systems developed by Annex 1 countries, those being developed by less
4826 developed countries will differ in their methods and data. However the results of all the
4827 systems should be comparable.

4828

4829 3.1.5 Estimation of uncertainties

4830 The majority of Annex-1 countries performed some uncertainty assessment for the
4831 LULUCF sector, but in most cases with tier 1 (error propagation), not covering the whole
4832 sector and often largely based on expert judgments (which are rather uncertain
4833 themselves). Estimated uncertainties are generally higher for emission factors (i.e.
4834 carbon stock changes for unit of area) than for activity data (i.e. area of different land
4835 uses), e.g. for "forest remaining forest" most of the reported uncertainties for the CO₂
4836 removals by the living biomass are between 25% and 50%, while for the forest area are
4837 generally lower than 25%. When estimated, uncertainties associated to land use changes
4838 and to emissions from the soil pool are typically higher. As example, the overall LULUCF

4839 uncertainty of the European Community (15 Member States) has been preliminary
4840 estimated around 40%.

4841

4842 Please refer to Section 2.6 for further information on uncertainty assessment.

4843

4844 **3.1.6 Key References for section 3.1**

4845

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4860 doi:10.1016/j.ecolmodel.2008.10.018.

4861 NCAS (National Carbon Accounting System of Australia). Description available at:
4862 www.climatechange.gov.au/ncas. For further information contact: Dr Gary
4863 Richards, Principal Scientist, National Carbon Accounting System, Department of
4864 Climate Change, Email: Gary.Richards@climatechange.gov.au,

4865

4866

4867 **3.2 OVERVIEW OF THE EXISTING FOREST AREA** 4868 **CHANGES MONITORING SYSTEMS**

4869 Frédéric Achard, Joint Research Centre, Italy.

4870 Ruth De Fries, Columbia University, USA

4871 Devendra Pandey, Forest Survey of India, India

4872 Carlos Souza Jr., IMAZON, Brazil

4873 **3.2.1 Scope of chapter**

4874 **This chapter presents an overview of the existing forest area changes**
4875 **monitoring systems at the national scale in tropical countries using remote**
4876 **sensing imagery.**

4877 Section 3.3.2 describes national case studies: the Brazilian system which produces
4878 annual estimates of deforestation in the legal Amazon, the Indian National biannual
4879 forest cover assessment, an example of a sampling approach in the Congo basin and an
4880 example of wall-to-wall approach in Cameroon.

4881 **3.2.2 National Case Studies**

4882 **3.2.2.1 Brazil – annual wall to wall approach**

4883 The Brazilian National Space Agency (INPE) produces annual estimates of deforestation
4884 in the legal Amazon from a comprehensive annual national monitoring program called
4885 PRODES.

4886 The Brazilian Amazon covers an area of approximately 5 million km², large enough to
4887 cover all of Western Europe. Around 4 million km² of the Brazilian Amazon is covered by
4888 forests. The Government of Brazil decided to generate periodic estimates of the extent
4889 and rate of gross deforestation in the Amazon, “a task which could never be conducted
4890 without the use of space technology”.

4891 The first complete assessment by INPE was undertaken in 1978. Annual assessments
4892 have been conducted by INPE since 1988. For each assessment 229 Landsat satellite
4893 images are acquired around August and analyzed. Results of the analysis of the satellite
4894 imagery are published every year. Spatially-explicit results of the analysis are also
4895 publicly available (see http://www.obt.inpe.br/prodes/prodes_1988_2007.htm).

4896 The PRODES project has been producing the annual rate of gross deforestation since
4897 1988 using a minimum mapping (change detection) unit of 6.25 ha. To be more detailed,
4898 and so as to profit from the dry weather conditions of the summer for cloud free satellite
4899 images, the project is carried out once a year, with the release of estimates foreseen in
4900 December of that same year. PRODES uses imagery from TM sensors onboard Landsat
4901 satellites, sensors of DMC satellites and CCD sensors from CBERS satellites, with a
4902 spatial resolution between 20m and 30m.

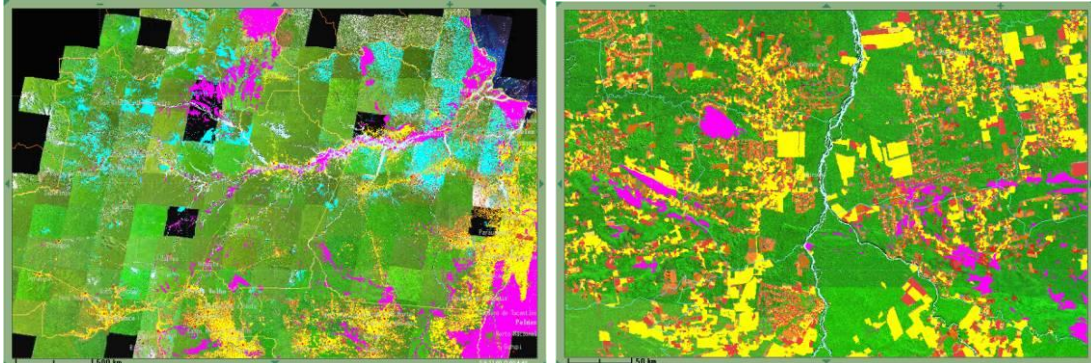
4903 PRODES also provides the spatial distribution of critical areas (in terms of deforestation)
4904 in the Amazon. As an example, for the period August 1999 to August 2000, more than
4905 80% of the deforestation was concentrated in 49 of the 229 satellite images analyzed.

4906

4907

4908 **Box 3.2.1: Example of result of the PRODES project:**

4909 Landsat satellite mosaic of year 2006 with deforestation during period 2000-2006
4910 Brazilian Amazon window Zoom on Mato Grosso (around Jurunea)
4911 (~3,400 km x 2,200 km) (~ 400 km x 30 km)



4912
4913 Forested areas appear in green, non-forest areas appear in violet, old deforestation
4914 (1997- 2000) in yellow and recent deforestation (from 2001) in orange-red.

4915
4916 A new methodological approach based on digital processing is now in operational phase.
4917 A geo-referenced, multi-temporal database is produced including a mosaic of deforested
4918 areas by States of Brazilian federation. All results for the period 1997 to 2008 are
4919 accessible and can be downloaded from the INPE web site at:
4920 <http://www.obt.inpe.br/prodes/>.

4921 Since May 2005, the Brazilian government also has in operation the DETER (Detecção de
4922 Desmatamento em Tempo Real) system to serve as an alert in almost real-time (every
4923 15 days) for deforestation events larger than 25 ha. The system uses MODIS data
4924 (spatial resolution 250m) and WFI data on board CBERS-2 (spatial resolution 260m) and
4925 a combination of linear mixture modeling and visual analysis. Results are publicly
4926 available through a web-site: <http://www.obt.inpe.br/deter/>.

4927
4928 In complement to its well-known deforestation monitoring system (PRODES) and its alert
4929 system (DETER), a new system has been developed in 2008 to monitor forest area
4930 changes within forests (forest degradation), particularly selective logging, named
4931 DEGRAD. The demand for DEGRAD emerged after recent studies confirmed that logging
4932 damages annually an area as large as the area affected by deforestation in this region
4933 (i.e., 10,000-20,000 km²/year). The DEGRAD system will support the management and
4934 monitoring of large forest concession areas in the Brazilian Amazon. The DEGRAD
4935 system is based on the detection of degraded areas detected from the DETER alarm
4936 system. As PRODES, DEGRAD is using Landsat TM and CBERS data with a minimum
4937 mapping unit of 6.25 ha. Degraded areas have been estimated for Brazilian Amazonia in
4938 2007 and 2008.

4939
4940 **3.2.2.2 India – Biennial wall to wall approach**

4941 The application of satellite remote sensing technology to assess the forest cover of the
4942 entire country in India began in early 1980s. The National Remote Sensing Agency
4943 (NRSA) prepared the first forest map of the country in 1984 at 1:1 million scale by visual
4944 interpretation of Landsat data acquired at two periods: 1972-75 and 1980-82. The
4945 Forest Survey of India (FSI) has since been assessing the forest cover of the country on
4946 a two year cycle. Over the years, there have been improvements both in the remote
4947 sensing data and the interpretation techniques. The 10th biennial cycle has just been

4948 completed from digital interpretation of data from year 2005 at 23.5 m resolution with a
 4949 minimum mapping unit of 1 ha. The details of the data, scale of interpretation,
 4950 methodology followed in wall to wall forest cover mapping over a period of 2 decades
 4951 done in India is presented in Table 3.4.

4952 The entire assessment from the procurement of satellite data to the reporting, including
 4953 image rectification, interpretation, ground truthing and validation of the changes by the
 4954 State/Province Forest Department, takes almost two years.

4955 The last assessment (X cycle) used satellite data from the Indian satellite IRS P6 (Sensor
 4956 LISS III at 23.5 m resolution) mostly from the period November-December (2004) which
 4957 is the most suitable period for Indian deciduous forests to be discriminated by satellite
 4958 data. Satellite imagery with less than 10% cloud cover is selected. For a few cases (e.g.
 4959 north-east region and Andaman & Nicobar Islands where availability of cloud free data
 4960 during Nov-Dec is difficult) data from January-February were used.

4961

4962 **Table 3.2.1. State of the Forest Assessments of India**

Assessment	Data Period	Satellite Sensor	Resolution	Scale	Analysis	Forest Cover Million ha
I	1981-83	LANDSAT-MSS	80 m	1:1 million	visual	64.08
II	1985-87	LANDSAT-TM	30 m	1:250,000	visual	63.88
III	1987-89	LANDSAT-TM	30 m	1:250,000	Visual	63.94
IV	1989-91	LANDSAT-TM	30 m	1:250,000	Visual	63.94
V	1991-93	IRS-1B LISSII	36.25 m	1:250,000	Visual	63.89
VI	1993-95	IRS-1B LISSII	36.25 m	1:250,000	Visual	63.34
VII	1996-98	IRS-1C/1D LISS III	23.5 m	1:250,000	digital/ visual	63.73
VIII	2000	IRS-1C/1D LISS III	23.5 m	1:50,000	digital	65.38
IX	2002	IRS-1D LISS III	23.5 m	1:50,000	digital	67.78
X	2004	IRS P6- LISS III	23.5 m	1:50,000	digital	67.70

4963

4964 Satellite data are digitally processed, including radiometric and contrast corrections and
 4965 geometric rectification (using geo-referenced topographic sheets at 1:50,000 scale from
 4966 Survey of India). The interpretation involves a hybrid approach combining unsupervised
 4967 classification in raster format and on screen visual interpretation of classes. The
 4968 Normalized Difference Vegetation Index (NDVI) is used for excluding non-vegetated
 4969 areas. The areas of less than 1 ha are filtered (removed).

4970 The initial interpretation is then followed by extensive ground verification which takes
 4971 more than six months. All the necessary corrections are subsequently incorporated.
 4972 Reference data collected by the interpreter during the field campaigns are used in the
 4973 classification of the forest cover patches into canopy density classes. District wise and
 4974 States/Union Territories forest cover maps are produced.

4975 Accuracy assessment is an independent exercise. Randomly selected sample points are
 4976 verified on the ground (field inventory data) or with satellite data at 5.8 m resolution and
 4977 compared with interpretation results. In the X assessment, 4,291 points were randomly
 4978 distributed over the entire country. The overall accuracy level of the assessment has
 4979 been found to be 92 %.

4980 India classifies its lands into the following cover classes:

4981

Very Dense Forest	All lands with tree cover of canopy density of 70% and above
Moderately Dense Forest	All lands with tree cover of canopy density between 40 % and 70 % above
Open Forest	All lands with tree cover of canopy density between 10 – 40 %.
Scrub	All forest lands with poor tree growth mainly of small or stunted trees having canopy density less than 10 percent.
Non-forest	Any area not included in the above classes.

4982

4983

4984 3.2.2.3 Congo basin – example of a sampling approach

4985 Analyses of changes in forest cover at national scales have been carried out by the
4986 research community. These studies have advanced methodologies for deforestation
4987 monitoring and provided assessments of deforestation outside the realm of national
4988 governments. As one example, a test of the systematic sampling approach has been
4989 carried out in Central Africa to derive area estimates of forest cover change between
4990 1990 and 2000. The proposed systematic sampling approach using mid-resolution
4991 imagery (Landsat) was operationally applied to the entire Congo River basin to
4992 accurately estimate deforestation at regional level and, for large-size countries, at
4993 national level. The survey was composed of 10 × 10 km² sampling sites systematically
4994 distributed every 0.5° over the whole forest domain of Central Africa, corresponding to a
4995 sampling rate of 3.3 % of total area. For each of the 571 sites, subsets were extracted
4996 from both Landsat TM and ETM+ imagery acquired in 1990 and 2000 respectively. The
4997 satellite imagery was analyzed with object-based (multi-date segmentation)
4998 unsupervised classification techniques.

4999 Around 60% of the 390 cloud-free images do not show any forest cover change. For the
5000 other 165 sites, the results are represented by a change matrix for every sample site
5001 describing four regrouped land cover change processes, e.g. deforestation, reforestation,
5002 forest degradation and forest recovery (the samples in which change in forest cover is
5003 observed are classified into 10 land cover classes, i.e. "dense forest", "degraded forest",
5004 "long fallow & secondary forest", "forest/agriculture mosaic", "agriculture & short fallow",
5005 "bare soil & urban area", "non forest vegetation", "forest-savannah mosaic", "water
5006 bodies" and "no data"). "Degraded forest" were defined spectrally from the imagery
5007 (lighter tones in image color composites as compared to dense forests – see next
5008 picture).

5009 For a region like Central Africa (with 180 Million ha), using 390 samples, corresponding
5010 to a sampling rate of 3.3 %, this exercise estimates the annual deforestation rate at
5011 0.21 ± 0.05 % for the period 1990-2000. For the Democratic Republic of Congo which is
5012 covered by a large-enough number of samples (267), the estimated annual deforestation
5013 rate was 0.25 ± 0.06 %. Degradation rates were also estimated (annual rate: $0.15 \pm$
5014 0.03 % for the entire basin).

5015 The accuracy of the image interpretation was evaluated from the 25 quality control
5016 sample sites. For the forest/non-forest discrimination the accuracy is estimated at 93 %
5017 ($n = 100$) and at 72 % for the 10 land cover classes mapping ($n = 120$). The overall
5018 accuracy of the 2 regrouped change classes, deforestation and reforestation, is
5019 estimated at 91 %. The exercise illustrates also that the statistical precision depends on
5020 the sampling intensity.

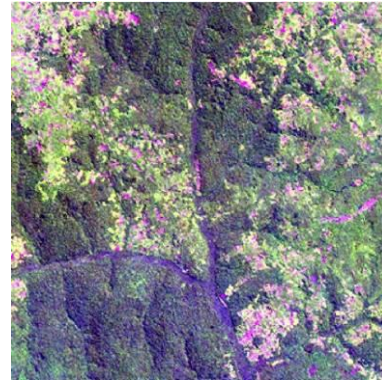
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5022

Box 3.2.2: Example of results of interpretation for a sample in Congo Basin

5023

Landsat image (TM sensor) year 1990 Landsat image (ETM sensor) year 2000



5024

Box size: 10 km x 10 km

Box size: 10 km x 10 km

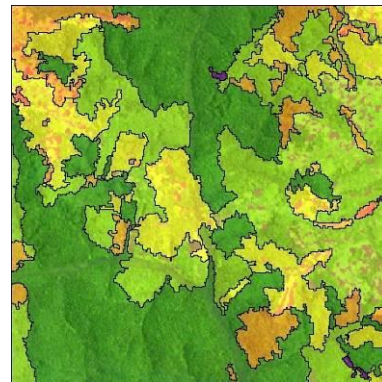
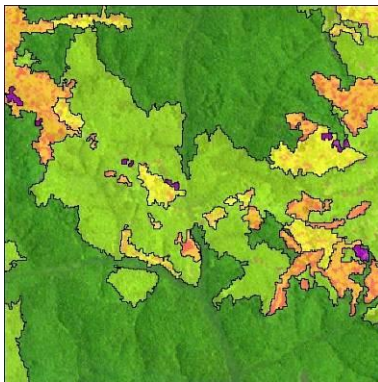
5025

5026

5027

Image interpretation of year 1990

Image interpretation of year 2000



5028

5029

5030

Legend: green = Dense forest, light green = degraded forest, yellow = forest/agriculture mosaic, orange = agriculture & fallow.

5031

5032

3.2.2.4 Cameroon – a wall-to-wall approach

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A REDD pilot project was initiated in Cameroon under the auspices of the Commission des Forêts d'Afrique Centrale - Central African Forestry Commission- (COMIFAC). This pilot aims at developing a framework for establishing historical references of emissions caused by deforestation, (using Earth Observation for mapping deforestation) combined with regional estimates of degradation nested in the wall-to-wall approach. Preliminary methodological testing in the transition zone between tropical evergreen forest and savannah in Cameroon has been completed⁵².

5040

5041

5042

5043

5044

Multi-temporal optical mid-resolution data (Landsat from years 1990 and 2000; DMC from year 2005) was used for the forest mapping in the test area. The method involves a series of three main processing steps: (1) cloud masking, geometric and radiometric adjustment, topographic normalization; (2) forest masking employing a hybrid approach including automatic multi-temporal segmentation, classification and manual correction

⁵² Hirschmugl M, Häusler T, Schardt M, Gomez S & Armathe JA 2008. REDD pilot project in Cameroon - Method development and first results. EaRSeL Conference 2008 Proceedings.

5045 and (3) land cover classification of the deforested areas based on spectral signature
5046 analysis⁵³.

5047

5048 **3.2.3 Key references for Section 3.2**

5049

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5059

5060

⁵³ www.gmes-forest.info

5061

5062 **3.3 NATIONAL FOREST INVENTORY: INDIA'S CASE** 5063 **STUDY**

5064 Devendra Pandey, Forest Survey of India, India

5065 **3.3.1 Scope of chapter**

5066 **Chapter 3.3 presents the Indian national forest inventory (NFI) as a case study**
5067 **for forest inventories in tropical countries**

5068 India has a long experience of conducting forest inventories at divisional / district level
5069 for estimating growing stock of harvestable timber. With a view to generate a national
5070 level estimate of growing stock in a short time and coincident with the biennial forest
5071 cover assessment based on satellite imagery, a new National Forest Inventory (NFI) was
5072 designed in 2001.

5073 **3.3.2 Introduction on forest inventories in tropical countries**

5074 Traditionally, forest inventories in several countries have been done to obtain a reliable
5075 estimate of the forest area and growing stock of wood for overall yield regulation
5076 purpose. The information was used to prepare the management plans for utilization and
5077 development of the forest resource and also to formulate the forest policies. The forest
5078 inventory provides data of the growing stock of wood by diameter class, number of the
5079 tree as well as the composition of species. Repeated measurement of permanent sample
5080 plots also provides the changes in the forest growing stock/ biomass.

5081 A number of sampling designs have been used to conduct the inventory, the most
5082 common of which are systematic sampling, stratified random sampling, and cluster
5083 sampling. The sampling designs, size and shape of the sample plots and the accuracy
5084 levels have depended on the situation of the forest resource, available time frame,
5085 budget allocation and available skilled human resource.

5086 In the developing region of the world several countries undertook one time inventory of
5087 their forests, usually at the sub-national level and some at the national level in a project
5088 mode in the past such as Myanmar⁵⁴, Malaysia, Indonesia, Bangladesh, Srilanka etc..
5089 There are, however, a few countries like India and China which are conducting the
5090 national forest inventory on a regular basis and have well established national institution
5091 for the same.

5092 India has a long experience of conducting forest inventory at divisional / district level
5093 which has forest area of about 1,000 km², mainly for estimating growing stock of
5094 harvestable timber needed for preparation of operational plan (Working Plan) of the
5095 area. The first working plan of a division was prepared in the 1860s and then gradually
5096 extended to other forest areas. The methodology for preparation was refined and quality
5097 improved with availability better maps and data. These inventories followed high
5098 intensity of sampling (at least 10%) but covered only a limited forest area (about 10 to
5099 15%) of a division supporting maturing crop where harvesting was to be done during the
5100 plan period of 10 to 15 years (Pandey, 2008).

⁵⁴ Shutter, H. 1984: National Forest Survey and Inventory of Burma (unpublished), input at 2nd Training Course in Forest Inventory, Dehradun, India

5101 The practice of preparing Working Plan for operational purposes continues even today by
5102 the provincial governments but the scale of cutting of trees has been greatly reduced
5103 due to increasing emphasis on forest conservation. With the availability of modern
5104 inventory tools and methods, a beginning has been made in a few provinces to inventory
5105 the total forest area of the division with low intensity of sampling mainly to assess the
5106 existing growing stock for sustainable forest management (SFM) and not only for
5107 harvesting of timber.

5108 In the Indian Federal set up, almost all the forests of the country are owned and
5109 managed by provincial governments. The Federal Government is mainly responsible for
5110 formulating policies, strategic planning, enact laws and provide partial financial support
5111 to provinces. Using the inventory data of the working plans it has not been possible to
5112 estimate growing stock of wood and other parameters of the forest resource at the
5113 province or national level.

5114 **3.3.3 Indian national forest inventory (NFI)**

5115 **3.3.3.1 Large scale forest inventories: 1965 to 2000**

5116 A relatively large scale comprehensive forest inventory was started by the Federal
5117 Government with the support of FAO/UNDP in 1965 using statistically robust approach
5118 and aerial photographs under a project named as Pre-Investment Survey of Forest
5119 Resources (PIS). The inventory aimed for strategic planning with a focus on assessing
5120 wood resource in less explored forests of the country for establishing wood based
5121 industries with a low intensity sampling (0.01%). The PIS inventory was not linked to
5122 Working Plan preparation nor was its data used to supplement local level inventory. The
5123 set up of PIS was subsequently re-organized into national forest monitoring system and
5124 a national institution known as Forest Survey of India (FSI) was created in 1981 with
5125 basic aim to generate continuous and reliable information on the forest resource of the
5126 country. During PIS period about 22.8 million ha of country's forests were inventoried
5127 (FSI 1996a). After the creation of the FSI, the field inventory continued with the same
5128 strength and pace as the PIS but the design was modified. The total area inventoried
5129 until the year 2000 was about 69.2 million ha, which includes some areas which were
5130 inventoried twice. Thus more than 80% forest area of the country was inventoried
5131 comprehensively during a period of 35 years. Systematic sampling has been the basic
5132 design under which forest area was divided into grids of equal size (2½' minute
5133 longitude by 2½' minute latitude) on topographic sheets and two sample plots were laid
5134 in each grid. The intensity of sampling followed in the inventory has been generally
5135 0.01% and sample plot size 0.1 ha

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5137 **3.3.3.2 National forest inventories from year 2001**

5138 With a view to generate a national level estimate of growing stock in a short time and
5139 coincident with the biennial forest cover assessment based on satellite imagery, a new
5140 National Forest Inventory (NFI) was designed in 2001. Under this programme, the
5141 country has been divided into 14 physiographic zones based on physiographic features
5142 including climate, soil and vegetation. The method involved sampling 10 percent of the
5143 about 600 civil districts representing the 14 different zones in proportion to their size.
5144 About 60 districts were selected to be inventoried in two years period. The first estimate
5145 of the growing stock was generated at the zonal and national level based on the
5146 inventory of 60 districts covered in the first cycle. These estimates are to be further
5147 improved in the second and subsequent cycles as the data of first cycle will be combined
5148 with second and subsequent cycles. The random selection of the districts is without
5149 replacement; hence each time new districts are selected (FSI 2008).

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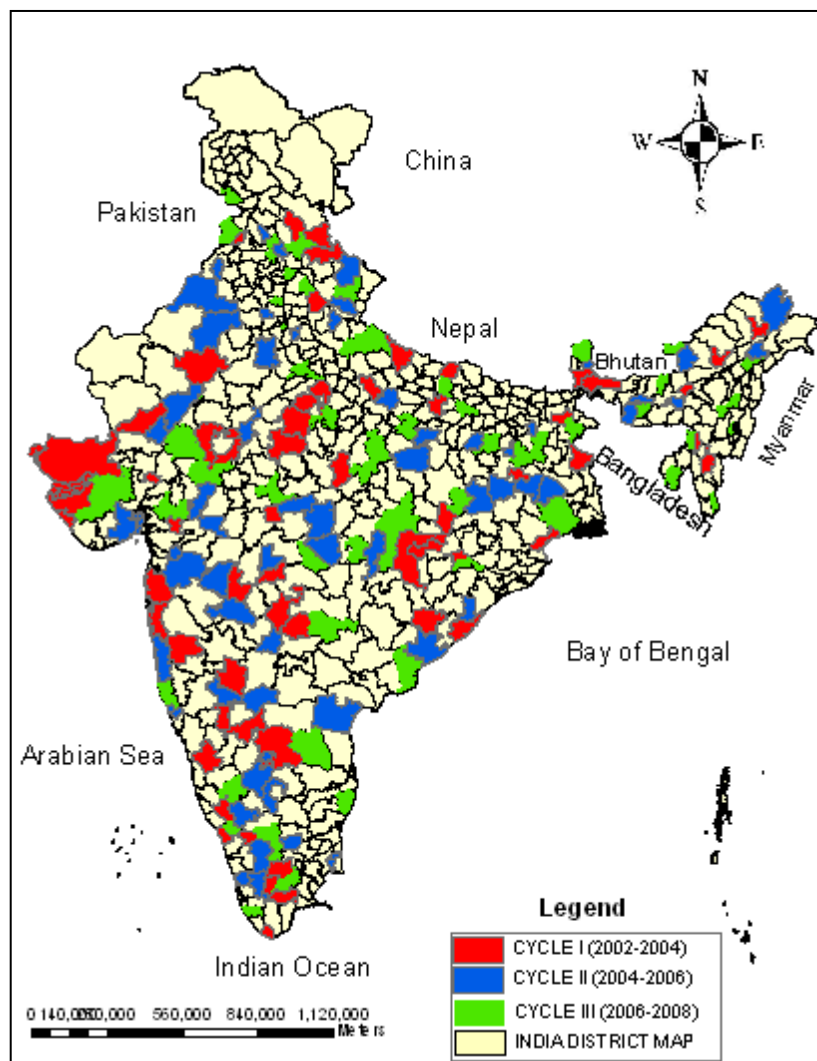
5151 **3.3.3.3 Field inventory**

5152 In the selected districts, all those areas indicated as Reserved Forests, Protected forests,
5153 thick jungle, thick forest etc, and any other area reported to be a forest area by the local
5154 Divisional Forest Officers (generally un-classed forests) are treated as forest. For each
5155 selected district, Survey of India topographic sheets of 1:50,000 scale are divided into
5156 36 grids of 2½' (minute longitude) by 2½' (minute latitude). Further, each grid is
5157 divided into 4 sub-grids of 1¼' by 1¼' forming the basic sampling frame. Two of these
5158 sub-grids are then randomly selected for establishing sample plots from one end of the
5159 sheet and then systematic sampling is followed for selecting other sub-grids. The
5160 intersection of diagonals of such sub-grids is marked as the center of the plot at which a
5161 square sample plot of 0.1 ha area is laid out to conduct field inventory (see two figures
5162 below for details).

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Figure 3.3.1: Selected districts under national forest inventory



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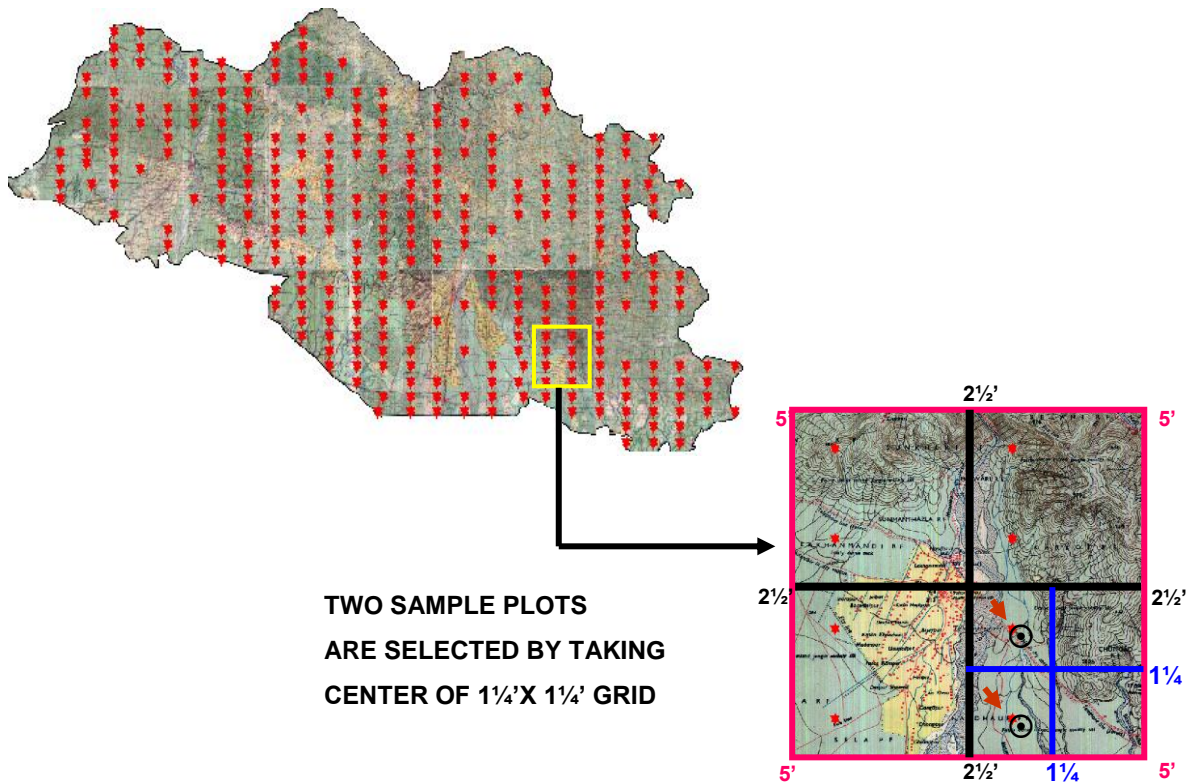
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Figure 3.3.2: Forest inventory points in one of the districts

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5174 Diameter at breast height (1.37 m) of all the trees above 10 cm (DBH) in the sample
 5175 plot and height as well as crown diameter of trees standing in only one quarter of the
 5176 sample plot are measured. In addition legal status, land use, forest stratum, topography,
 5177 crop composition, bamboo, regeneration, biotic pressure, species name falling in forest
 5178 area are also recorded. Two sub plots of 1 m² are laid out at the opposite corners of the
 5179 sample plot to collect sample for litter/ humus and soil carbon (from a pit of 30 cm x
 5180 30cm x 30cm). Further, nested quadrates of 3mx 3 m and 1mx1 m are laid at 30 m
 5181 distance from the center of the plot in all the four corners for enumeration of shrubs and
 5182 herbs to assess the biodiversity (FSI 2008).

5183 In two years about 7,000 sample plots representing different physiographic zones in the
 5184 60 selected districts are laid and inventoried. The field operations of NFI are executed
 5185 by the four zonal offices of the FSI located in different parts of the country. About 20
 5186 field parties (one field party comprise of one technician as leader, two skilled workers
 5187 and two unskilled workers) carryout inventory in the field at least for eight months in a
 5188 year. During the four rainy months the field parties carry out data checking and data
 5189 entry in the computers at the zonal headquarters. The data is then sent to the FSI
 5190 headquarters for further checking and processing. After manual checking of the sample
 5191 data in a random way, inconsistency check is carried out through a soft ware and then
 5192 data is processed to estimate various parameters of forest resource under the
 5193 supervision of senior professionals.

5194 For estimating the volume of standing trees FSI has developed volume equations for
 5195 several hundred tree species growing in different regions of the country (FSI, 1996b).
 5196 These equations are used to estimate the wood volume of the sample plots. Since
 5197 equations have been developed on the volume of trees measured above 10 cm diameter
 5198 at breast height (dbh) trees below 10 cm dbh are not measured and their volume not
 5199 estimated. Further for the trees above 10 cm dbh the volume of main stem below 10 cm
 5200 and branches below 5 cm diameter are also not measured. Thus the existing volume
 5201 equations underestimate the biomass of trees species. The above ground biomass of
 5202 other living plants (herbs and shrubs) is also not measured.

5203

5204 **3.3.3.4 Inventory for missing components of the forest biomass**

5205 As mentioned in the previous section the current national forest inventory (NFI) do not
5206 measure the total biomass of the trees, besides not measuring the biomass of herbs and
5207 shrubs, deadwood. Therefore, a separate nation wide exercise has been undertaken by
5208 FSI since August 2008 (FSI 2008) to estimate the biomass of missing components. In
5209 this exercise there are two components and both involve destructive sampling. One
5210 component is the measurements on individual trees for estimating volume of trees below
5211 10 cm diameter at breast height (dbh) and volume of branch below 5 cm and stem wood
5212 below 10 cm for trees above 10 cm dbh. Only about 20 important tree species in each
5213 physiographic zone are covered in this exercise. In all there will about 100 tree species
5214 at the nation level. The trees and their branches are cut and weighed in a specified
5215 manner to measure the biomass. New biomass equations are being developed for the
5216 trees species below 10 cm dbh. For the trees above 10 cm dbh the additional biomass
5217 measured through this exercise will be added to the biomass of tree species of
5218 corresponding dbh whose volume and biomass has already been estimated during NFI.

5219 In the second component sample plots are laid out for measuring volume of deadwood,
5220 herb shrub and climbers and litter. Because of the limitation of the time only minimum
5221 number of samples plots has been decided. In all only 14 districts in the country, that is,
5222 one district from each physiographic zone. While selecting districts (already inventoried
5223 under NFI) due care has been taken so that all major forest types (species) and canopy
5224 densities are properly represented. About 100 sample points are laid in each district. At
5225 national scale there will be about 1400 sample points. The geo-coordinates of selected
5226 sample points in each district are sent to field parties for carrying out the field work. In a
5227 stratum based on type and density about 15 sample plots are selected which gives a
5228 permissible error of 30%. At each sample plot three concentric plots of sizes 5mx5m for
5229 dead wood, 3mx3m for shrubs, climbers & litter and 1mx1m for herbs are laid (FSI
5230 2008). The deadwood collected from the sample plots are weighed in the field itself.
5231 Green weight of the shrubs, climbers and herbs cut from the ground is also taken which
5232 are later converted into dry weight by using suitable conversion factors.

5233

5234 **3.3.3.5 Estimation of costs**

5235 The total number of temporary sample plots laid out in the forests of 60 districts is about
5236 8,000 where measurements are completed in two years. The field inventory and the data
5237 entry are conducted by the zonal offices of the Forest Survey of India located in four
5238 different zones of the country. The data checking and its processing are carried out in
5239 FSI headquarters (Dehradun). The estimated cost of inventory per sample plot comes to
5240 about US\$ 158.00 uncluding travel to sample plot, field measurement including checking
5241 by supervisors and the rest on field preparation, equipment, designing, data entry,
5242 processing etc.

5243 The additional cost for estimating the missing components of biomass has been worked
5244 out to be about 52 US\$ per plot. This cost would be greatly reduced if the exercise of
5245 additional measurements is combined with regular activities of NFI. Moreover the
5246 biomass equations developed for trees below 10 cm dbh and that of above 10 cm is one
5247 time exercise. There will be no cast on this in future inventory.

5248 **3.3.4 Key references for Section 3.3**

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5267 **3.4 DATA COLLECTION AT LOCAL / NATIONAL LEVEL**

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5269 Observation (ITC), The Netherlands

5270 Margaret Skutsch, University of Twente, The Netherlands

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5272 **3.4.1 Scope of Chapter: rationale for community based inventories**

5273 Forest land in developing countries is increasingly being brought under community
5274 management under programmes such as Joint Forest Management, Community Based
5275 Forest Management, Collaborative Management, etc, more generally called Community
5276 Forest Management (CFM). This movement has been stimulated by the recognition in
5277 many countries that the Forest Department (FD), which is nominally responsible for
5278 management of state-owned forest, does not have the resources to carry out this task
5279 effectively. Rural people, whose livelihoods are supplemented by, or even dependent on,
5280 a variety of forest products such as firewood and fodder, foods and medicines, have the
5281 potential knowledge and human resources to provide effective management capacity to
5282 take care of the forest resources when the FD cannot. Whereas uncontrolled over-
5283 exploitation by outsiders, or the communities themselves, will lead to degradation and
5284 loss of biomass, CFM establishes formal systems between communities and FDs in which
5285 communities have the right to controlled amounts of forest products from a given parcel
5286 of forest and in return agree to protect the forest and manage it collectively. Mostly
5287 these parcels are relatively small, from 25 to 500 hectares, being managed by groups of
5288 10 to 50 households. A number of countries have used CFM very effectively to reverse
5289 deforestation and degradation processes. In Nepal, for example, 25% of all forest land is
5290 now more or less sustainably managed by so-called 'Forest User Groups'. Similar
5291 processes of forest governance are found on a smaller scale in many other developing
5292 countries, e.g. Tanzania, Cameroon, India and Mexico to name a few examples.

5293 This chapter presents how CFM groups and societies can carry out forest inventories, in
5294 particular if there is any prospect of payment for environmental services which require
5295 reliable, detailed measurements. Carbon services under REDD are a prime example, if
5296 communities are engaged in forest inventory work and rewarded for improvements in
5297 stock with benefits in cash or kind. Moreover, if communities measure the carbon stock
5298 changes in the forests they manage, they may establish 'ownership' of any carbon
5299 savings, to strengthen their stake in the REDD reward system and greatly increase
5300 transparency in the sub-national / intra-national governance of REDD finances.

5301 How the involvement of local communities in REDD will be achieved in individual
5302 countries is within the purview of the national government. Government philosophy, land
5303 ownership and tenure rights, competing claims on forest resources (e.g. commercial
5304 logging operations) all contribute to a variety of conditions that is untenable for a single
5305 solution. However, the requirements for large scale data collection in the field call for the
5306 meaningful involvement of local communities, if only to reduce the cost of the
5307 inventories.

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Box 3.4.1: Community Forest Management practice in Cameroon

In spite of the role of central government and forest legislation in Cameroon it should be noted that social institutions at community level in forest areas are still strongly rooted in rights based on kinship and descent. These rights are of central relevance to the understanding of contemporary issues of land tenure, agriculture and natural resource management and eventually the REDD process.

The state of Cameroon is the sole proprietor and manager of all forest resources. Nevertheless, in certain instances an agreement can be made between the state and a community or group of communities allowing them to manage the forest at their vicinity for their own benefit after the elaboration and acceptance of a management plan by the forest authorities. It is important to note that such a management convention neither grants the community property rights for the domain nor ownership rights for the forest resources. The ownership rights belong to the state and the benefits of the community are defined in the management plan.

In stark contrast, land ownership in the traditional land tenure system is based on succession and inheritance rights that are tied with genealogical rights. Even though these traditional land tenure values are not covered by statutory laws, indigenes of forest communities adhere with incredible tenacity to these "divine" rights. In order to involve communities in the implementation of the REDD process and to guarantee the sharing of benefits, it is of utmost importance to address this issue. A functional system to include effective community based participation is one that recognises the state as the main officiating organisation for all REDD activities, which includes the state's requirement for community participation and the state's obligation to equitably share revenues with the communities.

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Box 3.4.2: Community Forest Management in Ghana

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Until recently, legislative control in Ghana over land, particularly forest resources, was largely vested in the state, whilst custodial title to these resources remained in the stools, skin and families who hold the land in trust for their respective communities. In recognition of the role of local communities in sustainable management of land, the constitution of the Republic of Ghana has empowered and legalized the local communities through the District Assemblies in respect of the Local Government Act (Act 462) to actively court local communities, NGOs, civil society, etc. in the management and conservation of biodiversity. The process is being actively pursued through the Community Resource Management Area (CREMA) concept which seeks progressive devolution of power and management functions to local communities. Several projects and activities have been developed that have relevance to community involvement in REDD:

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- The GEF Small Grants Programme is supporting the Wildlife Division of the Forestry Commission to implement the CREMA concept by assisting local communities, NGOs and civil society, to manage wildlife and other natural resources in their own forests. This, in a way, is directly relevant to the REDD process as it will ensure sustained community ownership of the forest resources which ultimately will facilitate the data collection mechanisms for REDD activities. The GEF/SGP in Ghana has distinguished itself in assisting local communities to conserve biological diversity of forests outside the gazetted forest reserves, e.g. by creating buffer zones around sacred groves, rehabilitating degraded areas through enrichment planting and natural regeneration. To date about 200,000 ha of traditionally protected community forests have been conserved and new community natural resource management areas are being created and conserved.

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- The Geo-Information for Off-Reserve Tree Management in Goaso District (GORTMAN Project) was funded by Tropenbos International (TBI) as a collaborative research project among the University of Ghana, ITC (Netherlands), University of Freiburg (Germany), and the Resource Management and Support Centre of the Forestry Commission of Ghana (RSMC). This project built capacity in the Forestry Commission to manage large-scale data collection in basic forest properties by local communities, and to develop alternatives for tree felling in lands under control of the local chiefs.

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- The GEF-Funded Project "Sustainable Land Management for Mitigating Land Degradation, Enhancing Agricultural Biodiversity and Reducing Poverty" (SLAM) in Ghana, and its successor the GEF-Funded United Nations University (UNU) project "People, Land Management and Environmental Change" (PLEC) also successfully adopted participatory approaches which sought community entry via similar methods in the major agro-ecological zones in Ghana. This included establishment of sampling plots with residents undertaking the more rudimentary aspects of field data collection, e.g. tree species, tree count, DBH including, in some instances integration of hand-held GPS. Additional data collected within the scope of projects included vital-socio-economic data.

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Whilst there are no deliberate carbon stock measurements, efforts are being made by NGOs and university and research institutions to involve local communities in participatory activities for field data collection. The capacity of participating communities has been enhanced through training programmes including the Darwin programmes (UK) and local collaborators. REDD processes will offer great opportunities for local communities to have a sense of ownership over their forest resources thereby ensuring data accuracy and integrity. This will ensure their commitment beyond prevailing unattractive alternative livelihood packages being offered them by environmental NGOs. In these and other projects, successful entry has been initiated in close collaboration with local communities and their leaders.

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5394 **3.4.2 How communities can make their own forest inventories**

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5396 Forest inventory work is usually considered a professional activity requiring specialised
5397 forest education. However, it is well established already that local communities have
5398 extensive and intimate knowledge of ecosystem properties, tree species distribution, age
5399 distribution, plant associations, etc needed for inventories, and there is growing evidence
5400 that land users with very little professional training can make quite adequate and reliable
5401 stock assessments. In the Scolel Te project in Mexico, for example, farmers make their
5402 own measurements both of tree growth in the agroforestry system, and of stock
5403 increases in forests under their protection, and they receive (voluntary market) payment
5404 on the basis of this.

5405 The methodology for forest inventory here presented is based on procedures
5406 recommended in the IPCC Good Practice Guidelines, but structured in such a way that
5407 communities can carry out the different steps themselves without difficulty. Intermediary
5408 organizations are required to support some of the tasks, but such intermediary
5409 organizations are often already present and assisting communities in their forest
5410 management work. The procedures described have been tested at 35 sites in seven
5411 countries. Their reliability has been cross-checked using independent professional forest
5412 surveyors (see below in section 3.4.4). In all cases where cross-checking was carried
5413 out, the communities' estimates of mean forest carbon content differed by less than 5%
5414 from that of the professionals.

5415 Much of the work in forest inventory, at least as regards above ground woody biomass,
5416 is simple and repetitive and can be carried out by people with very little education,
5417 working in teams. The method described makes use of hand-held computers linked with
5418 GPS instruments that can be operated by people with as little as four years primary
5419 education. The benefit of this setup is the combination of the ease of plot biomass and
5420 other data recording in the computer with maps, aerial photos or satellite images visible
5421 on screen, together with the linked geo-positioning from the GPS. Though they may
5422 never have operated a computer before, village people almost everywhere are familiar
5423 with mobile phones, and find the step to hand-held computers quite easy. Some of the
5424 key activities need to be supervised by people with some understanding of statistical
5425 sampling and who can maintain ICT equipment. Many field offices of forestry
5426 organization or local NGOs are able to provide such supportive services. To
5427 institutionalize community forest inventories, such intermediaries first need to be trained
5428 in the methodology. These intermediaries would then train local communities to carry
5429 out many of the steps necessary, and oversee the process at least in the first few years
5430 in which the forest inventory is carried out. Certain activities, such as laying out the
5431 permanent sample plots, need expertise, but once they are established, annual
5432 measurements can be made by the villagers without assistance. Hence there will be
5433 higher costs in the initial years, but these fall rapidly over time. See Tables 3.4.1 and
5434 3.4.2 for an overview of the steps involved in this process for the intermediaries and the
5435 communities, respectively. Naturally, there will always be a need for independent
5436 verification of carbon claims; Section 3.4.6 considers the options for this.

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Table 3.4.1: Tasks requiring input from intermediary

Task	Who?	Equipment	Frequency	Description and comments
1. Identify forest inventory team members (4 to 7)	Intermediary in consultation with community leaders		At start	Need to include people who are familiar with the forest and active in its management; at least some must be literate/numerate. Ideally the same people will do the forest inventory work each year so that skills are developed and not lost. There is some danger of elite capture of the benefits, particularly if cash payments for carbon gains are to be made over to the community, attention must be given to this to ensure transparency within the community as a whole.
2. Programming PDA with base map, database & C calculator	Intermediary	PDA, internet	Once, at start of work	Any geo-referenced area map of suitable scale can scanned and entered into the PDA for use as the base map. Database format can be downloaded from website into PDA, as can the carbon calculator.
3. Map boundaries of community forest	Community, with intermediary assistance	PDA with GIS and GPS	Once, at start of work	Boundaries of many community forests are known to local people but not recorded on formal maps or geo-referenced. PDAs with built-in or attached GPS can easily be operated by local people to track and mark these boundaries on the base map, enabling area for forest to be calculated.
4. Identify and map any important forest strata	Community with intermediary assistance	PDA with GIS and GPS	Once, at start of work	Communities know their forests well. This step is best carried out by first discussing the nature of the forest and confirming what variations there may be within it (different species mix, different levels of degradation etc). Such zones can then be mapped by walking their boundaries with the GPS.
5. Pilot survey in each stratum to establish number of sample plots	Community with intermediary assistance	Tree tapes and/or calipers		The pilot survey is done with around 15 plots in each stratum. Measuring the trees in these plots could form the training exercise in which the intermediary first introduces the community forest inventory team to measurement methods.
6. Setting out permanent plots on map	Intermediary	Base map, calculator	Once, at start	This requires statistical calculation of number of plots needed, based on the standard error found in the pilot measurements. A tailor made programme for this is downloadable from the website and can be operated on the PDA. Plots are distributed systematically and evenly on a transect framework with a random start point.
7. Locating and marking sampling plots in the forest	Community with intermediary assistance	Map of plot locations, compass, GPS, tape measure, marking equipment	Once, at start	Community team stakes out the centres of the plots in the field by use of compass and measuring tape. GPS readings are recorded, and the centre of the plot is permanently marked (e.g. with paint on a ventral tree trunk). Each plot is given an identification code and details (identifying features) are entered into the PDA
8. Training community team how to measure trees in sample plots	Intermediary		+/- 4 days first time; 1 day for each of the next 3 years	This task could be fulfilled first time while carrying out task 5, see notes. The task involves listing and giving identification codes to the tree species found in the forest. It is expected that the community will be able to function independently in this task after year 4.
9. Identification of suitable allometric equations & programming into the PDA	Intermediary		Once, at start	The programme for the PDA contains default allometric equations. If local ones are available, these may be substituted, which will give greater accuracy.

10. Downloading from the PDA of forest inventory data & forwarding to registration	Intermediary			The PDA is programmed to make all necessary calculations and produce an estimate of the mean of the carbon stock in each stratum, with confidence levels (the default precision is set at 10%). This data needs to be transferred to more secure databases for comparison year to year and for eventual registration.
11. Maintaining PDA				PDA's require re-charging on a daily basis and minor repairs from time to time. It is anticipated that an intermediary would have several PDA's and would lend these to communities for the forest inventory work (around 10 days per community per year).

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5442 **Table 3.4.2: Tasks that can be carried out by the community team unaided after**
5443 **training**

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Task	Equipment	Frequency	Description and comments
Measure dbh (and height, if required by local allometric equations) of all trees of given minimum diameter in sample plots	Tree tapes or callipers	Periodically, e.g. annually	During the first year, fairly complete supervision by the intermediary is advisable, but in subsequent years a short refresher training will be sufficient, see above, task 8
Enter data into database (on paper sheets and/or on PDA)	Recording sheets/PDA	Periodically, e.g. annually	In some cases communities appear to find it easier to use pre-designed paper forms to record tree data in the field, although direct entry of data into the PDA is certainly possible and reduces chance of transcribing error.

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5447 **Box 3.4.3: Data collection at the community level**

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5449 There are many good reasons to include communities in the collection of data for
5450 REDD. Foremost are ownership and commitment: if the communities are involved
5451 and get a fair share of the benefits, then they will automatically become custodians
5452 of the forest and protect the local resources. More practically, community
5453 involvement is the most cost-efficient mechanism to collect large volumes of basic
5454 data. There are, however, limitations to the kind of data that communities can
5455 reliably collect, and the data is best limited to a small set of basic forest properties:

5456 • Species identification, with common names. (Botanical expert to convert
5457 common names to scientific nomenclature.) Periodic (e.g. once every five years).

5458 • Tree count. Annual.

5459 • DBH measurement. Annual.

5460 Even while reporting of carbon emission reduction is not done annually, it is
5461 important to collect the basic data annually. This maintains community
5462 involvement, but it is also a very important tool to assess the quality of the data
5463 collection process and it provides insight in the effectiveness of interventions to
5464 reduce emissions. Data quality assessment over time in a given community can be
5465 augmented by jointly analyzing the data from many communities in a single
5466 ecological zone or forest type. If a certain community is found to produce data that
5467 is divergent from that of the other communities then remedial action can be taken
5468 by investigating its cause:

5469 • Errors in the measurement procedure.

5470 • Errors in the stratification of the forest (e.g. forest belongs to a different
5471 ecological zone).

5472 • Effectiveness of intervention (improved forest management) is different.

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5474 Equipment (PDAs equipped with simple GIS software such as ArcPad™ and GPS
5475 attachments; measuring tapes, tree tapes, callipers etc) is assumed to be property of
5476 the intermediaries and used by a number of villages/community forest groups in a given
5477 area. An intermediary with one PDA could service between 12 and 20 communities per
5478 year (for cost estimates see Section 3.4.5). Appropriate methodology has been
5479 developed by the Kyoto:Think Global Act Local project and can be downloaded from the
5480 project website (see Box 3.4.4).

5481 Communities should be assisted in establishing the sampling plots. Marking of the centre
5482 of the permanent plots, for instance with paint on tree trunks, increases the reliability of
5483 the inventory and reduces the standard error by ensuring that exactly the same areas
5484 are measured each year. On the other hand, it could introduce bias in that it shows
5485 where the measurements are made, and could lead forest users to avoid these areas
5486 when e.g. collecting firewood or poles, thus reducing the representativeness of the
5487 sample. Using a GPS could be an alternative, but in densely forested areas the signal
5488 tends to be weak, giving a coarse determination of position.

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Box 3.4.4: The “Kyoto: Think Global, Act Local” collaborative research project

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The “Kyoto: Think Global, Act Local” research project has been piloting many of the techniques elaborated in this section. The KTGAL project is a joint endeavour of research institutes and NGOs in seven countries in Asia and Africa, led by the University of Twente of The Netherlands with the support of ITC, The Netherlands.

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The KTGAL project has prepared manuals intended for the training of intermediary staff in participatory forest inventory. It is assumed most staff would have had at least some intermediate (middle school) education, and that they are familiar with computers, but it is not a requirement that they have much forestry experience. The manuals can be downloaded from www.communitycarbonforestry.org, where you can also find other supporting information.

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3.4.3 Additional data requirements

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The communities are clearly in a position to collect basic data from the forest, such as tree species, tree count and DBH. However, the measurements are not always of high quality, over time, between stands or between observers. Furthermore, these data alone are not sufficient to compute above-ground biomass. It is therefore necessary to have a parallel process to supplement the basic data and to be able to ascertain the quality of the locally collected data.

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The additional data required depends on the local conditions and prior information. For instance, it is likely that locally derived allometric equations are used to calculate above-ground biomass and those equations may require input parameters like tree height, free branch height, or wood density. Such parameters could be collected using more traditional forest inventory techniques, such as those described in sections 2.3 and 3.3.⁵⁵

5516

3.4.4 Reliability and accuracy

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In order to test the reliability of community carbon stock estimates, independent professional forest companies were employed by the KTGAL project to carry out surveys in three of the project sites. In every case, there was no more than 5% difference in the estimate of mean carbon levels between the professionals and the community.

5521
5522
5523

It is recommended that communities make annual measurements, even though REDD credits may be issued only at the end of a five year commitment period. There are a number of reasons for this:

5524
5525
5526
5527

- If forests are measured annually, communities will be more aware of changes in the forest, moreover they will not forget how to make the measurements.
- Annual fluctuations due to weather changes are common; a five year trajectory enables these to some extent to be smoothed out.

⁵⁵ Even if no additional parameters are required beyond DBH, it is important to have a parallel process to measure DBH and tree counts with high accuracy, in order to validate the input received from communities. Standard statistical techniques can then be applied to establish whether or the data received from communities is reliable or not. Such an independent assessment is necessary to filter out errors in measurement and reporting, but also to establish the accuracy of the local data.

- 5528 • Any errors of measurement in a particular year may be more easily detected and
5529 eliminated. Annual measurement provides a robust approach to inventory.
- 5530 • It is likely that national REDD programmes will have to offer annual incentives for
5531 carbon savings rather than end-of-commitment-period payments, as communities
5532 are unlikely to accept a five year waiting period.

5533 The confidence level used in determining the number of sample plots is a major factor in
5534 the cost of carrying out forest inventory work. A confidence level of 95% rather than
5535 90% requires many more sample plots (i.e. more work by communities in making
5536 measurements). On the other hand, less uncertainty in the assessment of above-ground
5537 carbon will most likely lead to higher carbon emission reduction estimates and thus
5538 higher payments. Inversely, if the error in the data, established through statistical
5539 analysis, is high, then the error margins at the onset and end of the reporting period
5540 may overlap, and no carbon credits will be issued; see [Section 2.5](#) for more details.

5541

5542 To determine the number of sampling plots, given a certain confidence level and
5543 maximum error, one can apply the following formula:

5544 **(Equation 4.4.1)**
$$n = \left(\frac{z^* \cdot \sigma}{e \cdot \mu} \right)^2$$

5545 where z^* is the distribution critical value at a certain confidence level (published in any
5546 textbook on statistics), σ is the standard deviation, e is the maximum allowable error,
5547 and μ is the average biomass in the forest stratum.

5548 For a forest where μ is 400 t/ha with σ is 65 t/ha, if you want to have an error of at most
5549 5%, with 90% confidence level ($z^* = 1.645$):

5550
$$n = \left(\frac{1.645 \cdot 65}{0.05 \cdot 400} \right)^2 = 28.58 = 29$$

5551 For a 95% confidence level ($z^* = 1.960$):

5552
$$n = \left(\frac{1.960 \cdot 65}{0.05 \cdot 400} \right)^2 = 40.58 = 41$$

5553 Inversely, given a certain number of samples, the expected error can be calculated:

5554 **(Equation 4.4.2)**
$$e = \frac{z^* \cdot \sigma}{\sqrt{n \cdot \mu}}$$

5555 In all cases the average biomass in the forest μ and its standard deviation σ need to be
5556 established first. This is best done by professional foresters, using generally accepted
5557 techniques for sampling. In practice this implies a minimum of 30 randomly located
5558 samples per forest stratum.

5559

5560 Protocols regarding confidence levels are likely to be adopted nationally. The number of
5561 samples required to reach that confidence level given a certain maximum error for each
5562 forest (type) should be determined by a professional organization, e.g. a Forest
5563 Department, using accepted statistical practice. It can be reduced by careful
5564 stratification of forest ecosystem / type, because that will reduce the standard deviation
5565 of the samples in each stratum, and this is strongly recommended.

5566 **3.4.5 Costs**

5567 The KTGAL project estimated costs of community forest inventory as ranging between \$1
5568 and \$4 per hectare per year, including day wages for the community members involved
5569 and the intermediary, and a factor for 'rental' of the equipment (PDA, GPS, etc). The
5570 costs in the first year are higher than this, given the substantial inputs by the
5571 intermediary in training community members and establishment of the sampling plots.
5572 Average costs are much lower in large, homogeneous forests owing to economies of
5573 scale. The equivalent costs if professional organizations were to be employed instead of
5574 communities are two to three times higher than this.

5575 Carbon may be credited on a longer time interval (e.g. 5 years), but local communities
5576 need to be paid annually or even more frequent to maintain their commitment to the
5577 process. How payments are effectuated and on what basis is up to the government.
5578 Essentially there are three options:

- 5579 1. Communities implement activities to stop deforestation and reduce forest
5580 degradation and regularly inventory the forest to assess the amount of biomass.
5581 Payment is for the actual amount of emission reductions or forest enhancement.
5582 There is positive feedback from effective forest management by the communities
5583 (more payment) but it will be very difficult to administer such an arrangement.
5584 Payments will have to be made prior to receipt of CERs by the government in order
5585 to maintain community involvement.
- 5586 2. Inventories done by communities are paid for by government, as compensation for
5587 the effort made by the communities. There is thus no link with reductions in
5588 emissions or carbon sequestration – or increased emissions for that matter –
5589 payment is made for services rendered. This is probably the easiest to implement but
5590 it is a "dumb" approach; the communities are not rewarded for activities that lead to
5591 reducing emissions or enhancing the forest.
- 5592 3. Inventories are done by government who indemnify the communities for loss of
5593 opportunities (i.e. right to extract timber or NTFPs). This may be the preference by
5594 governments that to date have a strong and active Forest Department, but it does
5595 not address the cause of prior deforestation or forest degradation.

5596 **3.4.6 Options for independent assessment of locally collected data**

5597

5598 National governments will probably want to have an independent mechanism to verify
5599 the claims made by local communities. One of the options is statistical analysis, as
5600 briefly explained above, but at larger scales remote sensing would be an obvious choice;
5601 see Sections 2.1 and 2.2. In order to enable such assessments, forest organizations
5602 should make more complete inventories at the time of establishing the sampling scheme
5603 for community carbon assessments. A proper stratification of the forest, with due
5604 consideration for those properties of the forest that are easily detected on satellite
5605 imagery, will be of prime importance, as will be the detailed description of the forest
5606 structure.

5607 The data that are being collected by the communities can be correlated to satellite
5608 imagery using a number of techniques. The first one looks at the (assumed)
5609 homogeneity of the strata in the forest, while the second one establishes the correlation
5610 between biomass as measured in the forest and reflectance recorded in the satellite
5611 image:

- 5612 • Assuming that the stratification of the forest has led to homogenous units, the
5613 reflectance characteristics of the pixels in the stratum will be similar as well at the
5614 time the stratification is made (i.e. it has a uniform look in the imagery). At a
5615 later stage, when some management intervention has been implemented and the
5616 communities are collecting data, a new image can be analyzed for its uniformity.

5617 If the uniformity is no longer present, or weaker than before, it may be that part
5618 of the forest was deforested or some communities are not managing the forest as
5619 they should (but see also Box 3 for other potential causes). Please note that the
5620 reflectance itself may have changed if the biomass changed, either through
5621 continued but reduced degradation or because of forest enhancement.
5622 Homogeneity, and thus uniformity in the satellite image, may also increase if the
5623 forest is more uniformly degraded or enhanced; this may be avoided by applying
5624 a more strict stratification initially.

5625 • Using a standard image analysis technique, the biomass assessment made by the
5626 communities can be correlated to the reflectance in the satellite image. In open
5627 woodlands and forest types that have a distinct seasonal dynamic (e.g. leaf
5628 shedding in the dry season) the assessment (timing) has to be compatible with
5629 the measurements made by the local community. Outliers in the correlation
5630 indicate some issue with the data collection process (or deficient stratification).
5631 When widely implemented, the sheer volume of locally collected data, probably
5632 even when a detailed stratification of the forest is made, makes it possible to use
5633 only a (random) sample of the local data.

5634 **3.4.7 Options for independent assessment of locally collected data**

5635

5636 Future scenarios include the demand for additional types of information on CF which
5637 might be required under REDD directives:

- 5638 • Local / indigenous information on forest ecosystem – maybe needed under REDD
5639 systems for landscape-level allocation of funds under sub-national governance of
5640 REDD finances
- 5641 • Local / indigenous information on type and quality of management and their
5642 indicators – maybe needed under REDD systems for allocating funds according to
5643 types and quality of forest management.

5644 The great technological potential lies in the probable future ubiquity and reduced costs of
5645 mobile IT which will have greatly increased functionalities (at lower cost) and will be
5646 much easier to handle.

5647 • The smart phone with large memory (with a card) for storing the necessary
5648 imagery or maps, with GPS capability of reasonable precision, and with the web
5649 capacity for downloading images and uploading data can replace the PDA set-up.
5650 Major advantage is ease of use, convenience of supply and repair, and especially
5651 utilising the existing familiarity of ordinary people with cell phones – very easy for
5652 young community members to 'upgrade' to a smart phone. Currently, costs are
5653 high, but not prohibitive compared to PDA and GPS, and the business plan /
5654 concept is that the local intermediaries / brokers would be the resource holders of
5655 smart phones until such time as unit prices will drop.

5656 • Software with very user-friendly interface between users and the PDA or smart
5657 phone is being adapted for carbon measurement, with special attention to
5658 illiterate users, via application of icons and simplified data recording and clear
5659 sequential instructions.

5660

5661 **3.5 RECOMMENDATIONS FOR COUNTRY CAPACITY**
5662 **BUILDING**

5663 Sandra Brown, Winrock International, USA

5664 Martin Herold, Friedrich Schiller University Jena, Germany

5665 **3.5.1 Scope of chapter**

5666 Countries currently undertake national forest monitoring driven by a number of
5667 motivations from economic, socio-cultural and environmental perspectives. In most
5668 developing countries, however, the quality of current forest monitoring is considered not
5669 satisfactory for an accounting system of carbon credits (Holmgren et al. 2007). The
5670 development of forest monitoring systems for REDD is a fundamental requirement and
5671 area of investment for participation in the REDD process. Despite the broader benefits of
5672 monitoring national forest resources per se, there is a set of specific requirements for
5673 establishing a national forest carbon monitoring system for REDD implementation. They
5674 include:

- 5675 • The considerations of a national REDD implementation strategy;
- 5676 • Systematic and repeated measurements of all relevant forest-related carbon
5677 stock changes. Robust and cost-effective methodologies for such purpose are
5678 existing (UNFCCC, 2008a);
- 5679 • The estimation and reporting of carbon emissions and removals on the national
5680 level using the IPCC Good Practice Guidelines on Land Use Land Use Change and
5681 Forestry given the related requirements for transparency, consistency,
5682 comparability, completeness, and accuracy;
- 5683 • The encouragement for the monitoring systems and results to review
5684 independently.

5685 The design and implementation of a monitoring system for REDD can be understood as
5686 investment in information that is essential for a successful implementation of REDD. This
5687 chapter provides a more detailed description of required steps and capacities building
5688 upon the GOF-C-GOLD sourcebook recommendations.

5689 **3.5.2 Building National Carbon Monitoring Systems For REDD:**
5690 **Elements and Capacities**

5691 **3.5.2.1 Key elements and required capacities**

5692 The development of a national monitoring system for REDD is a process. A summary of
5693 key components and required capacities for estimating and reporting emissions and
5694 removals from forests is provided in Table 3.5.1. The first section of planning and design
5695 should specify the monitoring objectives and implementation framework based on the
5696 understanding of:

- 5697 • The status of international UNFCCC decisions and related guidance for monitoring
5698 and implementation;
- 5699 • The national REDD implementation strategy and objectives;
- 5700 • Knowledge in the application of IPCC LULUCF good practice guidelines;
- 5701 • Existing national forest monitoring capabilities;
- 5702 • Expertise in estimating terrestrial carbon dynamics and related human-induced
5703 changes;

5704 • The consideration of different requirements for monitoring forest changes in the
5705 historical (reference period) and for the future (accounting period);

5706 The planning and design phase should result in a national REDD monitoring framework
5707 (incl. definitions, monitoring variables, institutional setting etc.), and a plan for capacity
5708 development and long-term improvement and the estimation of anticipated costs.

5709
5710 Implementing measurement and monitoring procedures to obtain basic information to
5711 estimate GHG emissions and removals requires capabilities for data collection for a
5712 number of variables. Carbon data derived from national forest inventories and
5713 permanent plot measurements, and remote sensing-based monitoring (primarily to
5714 estimate activity data) are most commonly used. In addition, information from the
5715 compilations of forest management plans, independent reports, and case studies and/or
5716 models have provided useful forest data for national monitoring purposes. Irrespective of
5717 the choice of method, the uncertainty of all results and estimates need to be quantified
5718 and reduced as far as practicable. A key step to reduce uncertainties is the application of
5719 best efforts using suitable data source, appropriate data acquisition and processing
5720 techniques, and consistent and transparent data interpretation and analysis. Expertise is
5721 needed for the application of statistical methods to quantify, report, and analyze
5722 uncertainties, the understanding and handling of error sources, and approaches for a
5723 continuous improvement of the monitoring system both in terms of increasing certainty
5724 for estimates (i.e. move from Tier 2 to Tier 3) or for a more complete estimation (include
5725 additional carbon pools).

5726
5727 All relevant data and information should be stored, updated, and made available through
5728 a common data infrastructure, i.e. as part of national GHG information system. The
5729 information system should provide the basis for the transparent estimation of emissions
5730 and removals of greenhouse gases. It should also help in analysis of the data (i.e.
5731 determining the drivers and factors of forest change), support for national and
5732 international reporting using a common format of IPCC GPG 'reporting tables', and in the
5733 implementation of quality assurance and quality control procedures, perhaps followed by
5734 an expert peer review.

5735

5736 **Table 3.5.1: Components and required capacities for establishing a national**
5737 **monitoring system for estimating emissions and removals from forests.**

Phase	Component	Capacities required
Planning & design	1. Need for establishing a forest monitoring system as part of a national REDD implementation activity	<ul style="list-style-type: none"> • Knowledge on international UNFCCC decisions and SBSTA guidance for monitoring and implementation • Knowledge of national REDD implementation strategy and objectives
	2. Assessment of existing national forest monitoring framework and capacities, and identification of gaps in the existing data sources	<ul style="list-style-type: none"> • Understanding of IPCC LULUCF estimation and reporting requirements • Synthesis of previous national and international reporting (i.e. UNFCCC national communications & FAO Forest Resources Assessment) • Expertise in estimating terrestrial carbon dynamics, related human-induced changes and monitoring approaches • Expertise to assess usefulness and reliability of existing capacities, data sources and information
	3. Design of forest monitoring system driven by UNFCCC reporting requirements with objectives for historical period and future monitoring	<ul style="list-style-type: none"> • Detailed knowledge in application of IPCC LULUCF good practice guidelines • Agreement on definitions, reference units, and monitoring variables and framework • Institutional framework specifying roles and responsibilities • Capacity development and long-term improvement planning • Cost estimation for establishing and strengthening institutional framework, capacity development and actual operations and budget planning
Monitoring	4. Forest area change assessment (activity data)	<ul style="list-style-type: none"> • Review, consolidate and integrate the existing data and information • Understanding of deforestation drivers and factors • If historical data record insufficient – use of remote sensing: <ul style="list-style-type: none"> ○ Expertise and human resources in accessing, processing, and interpretation of multi-date remote sensing imagery for forest changes ○ Technical resources (Hard/Software, Internet, image database)

		<ul style="list-style-type: none"> ○ Approaches for dealing with technical challenges (i.e. cloud cover, missing data)
	5. Changes in carbon stocks	<ul style="list-style-type: none"> ● Understanding of processes influencing terrestrial carbon stocks ● Consolidation and integration of existing observations and information, i.e. national forest inventory or permanent sample plots: <ul style="list-style-type: none"> ○ National coverage and carbon density stratification ○ Conversion to carbon stocks and change estimates ● Technical expertise and resources to monitor carbon stock changes: <ul style="list-style-type: none"> ○ In-situ data collection of all the required parameters and data processing ○ Human resources and equipment to carry out field work (vehicles, maps of appropriate scale, GPS, measurements units) ○ National inventory/permanent sampling (sample design, plot configuration) ○ Detailed inventory in areas of forest change or “REDD action” ○ Use of remote sensing (stratification, biomass estimation) ● Estimation at sufficient IPCC Tier level for: <ul style="list-style-type: none"> ○ Estimation of carbon stock changes due to land use change ○ Estimation of changes in forest areas remaining forests ○ Consideration of impact on five different carbon pools
	6. Emissions from biomass burning	<ul style="list-style-type: none"> ● Understanding of national fire regime and fire ecology, and related emission for different greenhouse gases ● Understanding of slash and burn cultivation practice and knowledge of the areas where being practiced ● Fire monitoring capabilities to estimate fire effected area and emission factors: <ul style="list-style-type: none"> ○ Use of satellite data and products for active fire and burned area ○ Continuous in-situ measurements (particular emission factors)
	7. Accuracy assessment and verification	<ul style="list-style-type: none"> ● Understanding of error sources and uncertainties in the assessment process ● Knowledge on the application of best efforts using appropriate design, accurate data collection, processing techniques, and consistent and transparent data interpretation and analysis ● Expertise on the application of statistical methods to quantify, report and analyze uncertainties for all relevant information (i.e. area change, change in carbon stocks etc.) using, ideally, a sample of higher quality information
Analysis & reporting	8. National GHG information system	<ul style="list-style-type: none"> ● Knowledge on techniques to gather, store, and analyze forest and other data, with emphasis on carbon emissions from LULUCF ● Data infrastructure, information technology (suitable hard/software) and human resources to maintain and exchange data and quality control
	9. Analysis of drivers and factors of forest change	<ul style="list-style-type: none"> ● Understanding and availability of data for spatio-temporal processes affecting forest change, socio-economic drivers, spatial factors, forest management and land use practices, and spatial planning ● Expertise in spatial and temporal analysis and use of modeling tools
	10. Establishment of reference emission level and regular updating	<ul style="list-style-type: none"> ● Data and knowledge on deforestation and forest degradation processes, associated GHG emissions, drivers and expected future developments ● Expertise in spatial and temporal analysis and modeling tools ● Specifications for a national REDD implementation framework
	11. National and international reporting	<ul style="list-style-type: none"> ● Expertise in accounting and reporting procedures for LULUCF using the IPCC GPG ● Consideration of uncertainties and understanding procedures for independent international review

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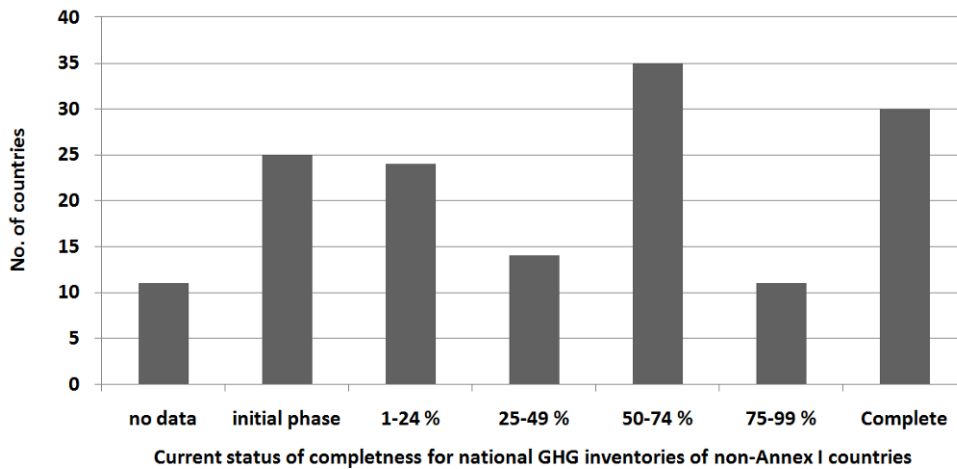
5739 3.5.2.2 Key elements and required capacities

5740 The discussion of requirements and elements (see Table 3.5.1) emphasize that
5741 comprehensive capacities are required for the measuring and monitoring, and the
5742 estimation, accounting and reporting of emissions and removals of GHG from forest land.
5743 So far, non-Annex I countries were not required to establish a GHG inventory. However,
5744 the development of UNFCCC national communications has stimulated support and
5745 engagement for countries to establish national GHG inventories and related national
5746 estimation and reporting capacities. Figure 2.1 highlights the current status and the
5747 range of completeness for national GHG inventories. About 1/5 of non-Annex I countries
5748 are listed with a fully developed inventory. An additional 46 countries have taken
5749 significant steps with inventories in the range of 50-100 % complete. About half of the
5750 countries currently have systems less than 50 % complete. Although the information in
5751 Figure 3.5.1 refers to the establishment of full GHG inventories, where the LULUCF
5752 sector is only one component, Figure 3.5.1 provides a sense of a current capacity gap for
5753 national-level GHG estimating and reporting procedures using the IPCC GPGs.

5754

5755

5756 **Figure 3.5.1:** Status for completing national greenhouse gas inventories as part of
5757 Global Environment Facility support for the preparation of national communications of
5758 150 non-Annex I countries (UNFCCC, 2008b).



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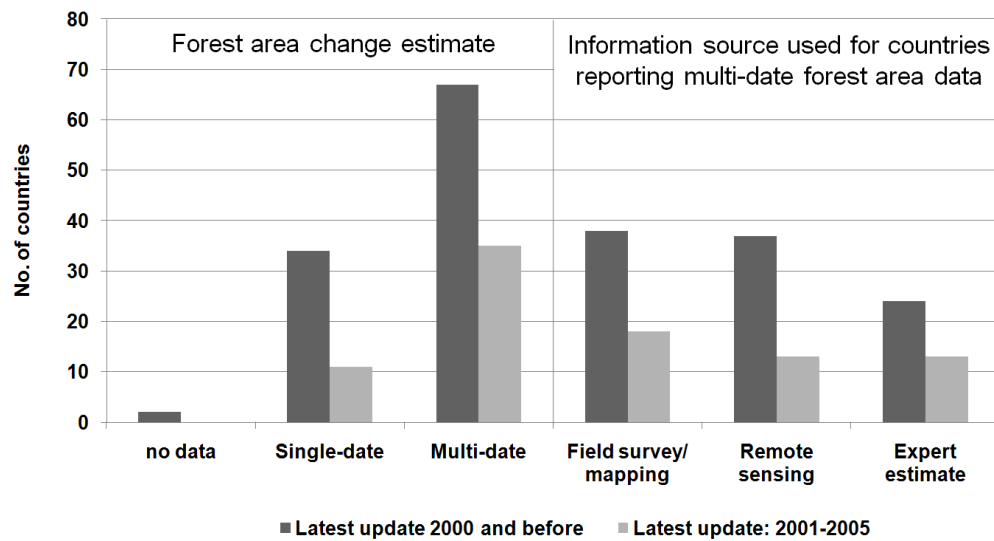
5761 A status of country capacities for the monitoring of forest area change and changes in
5762 forest carbon stocks may be inferred from analyzing the most recent FAO global Forest
5763 Resources Assessment (FRA) for 2005 (FAO 2006). Assuming that all available and
5764 relevant information have been used by countries to report under the FRA, Figures 3.5.2
5765 and 3.5.3 summarize the relevant capacities for non-Annex I countries.

5766 In terms of monitoring changes in forest area, Figures 3.5.2 highlights that almost all
5767 non-Annex I countries were able to provide estimate forest area and changes. About
5768 two-thirds of countries provided this information based on multi-date data; about one-
5769 third reported based on single-date data. Most of the countries used data from the year
5770 2000 or before as most recent data point for forest area, while 46 of 149 countries we
5771 able to supply more recent estimates. Of the countries that used multi-date information
5772 there is an almost even distribution for the use of information sources between field
5773 surveying and mapping, remote sensing-based approaches, and, with less frequency, for
5774 expert estimates (Note: countries may have used multiple sources).

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Figures 3.5.2: Summary of data and information sources used by 150 non-Annex I countries to report on forest area change for the FAO FRA 2005 (FAO 2006).

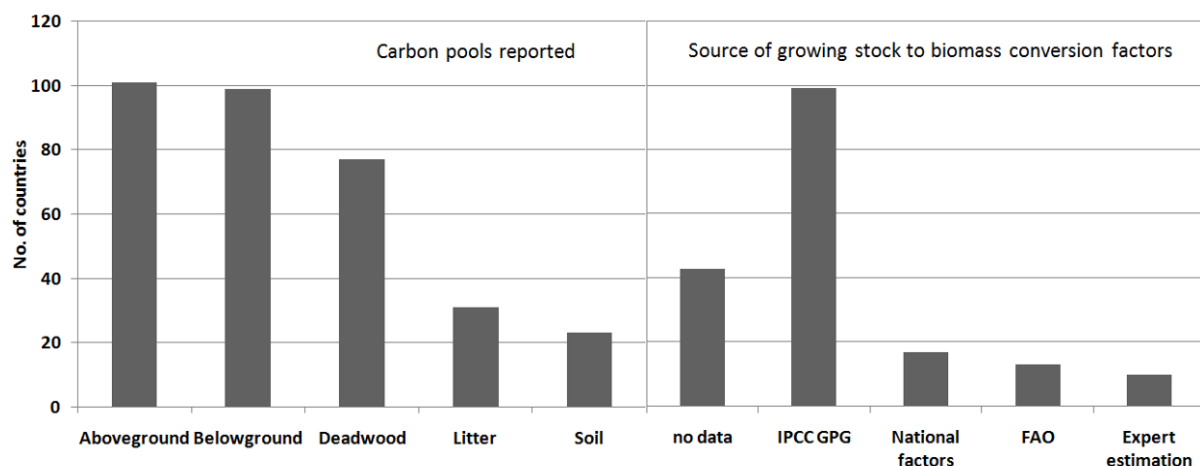


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A smaller number of countries provided estimates for carbon stocks (Figure 3.5.3). 101 of 150 countries reported on the overall stocks in aboveground carbon pool. Since the aboveground and belowground carbon pools are correlated almost the same number of countries reported on the carbon in below ground vegetation. Fewer countries were able to provide data on the other pools, in particular for carbon in the soils 23 (countries). The reported forest carbon pool estimates are primarily based on growing stock data as primary observation variable. Of the 150 non-Annex countries, 41 reported no growing stock data. 75 countries provided single-date and 34 multi-date growing stock data. A number of different sources are applied by countries for converting growing stocks to biomass (and to carbon in the next step), with the IPCC GPG default factors being used most commonly (Figure 3.5.3). The use of these default factors would refer to a Tier 1 approach for estimating carbon stock change using the IPCC GPG. Only 17 countries converted growing stock to biomass using specific and, usually, national conversion factors.

5795

Figure 3.5.3: Summary of data for five different carbon pools reported (left) and information sources used by 150 non-Annex I countries to convert growing stocks to biomass (right) for the FAO FRA 2005 (FAO 2006, countries may have used multiple sources for the conversion process).



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5801

5802 Figures 3.5.2 & 3.5.3 emphasize the varying level of capacities among non-Annex I
5803 countries. Given the results of FAO's FRA 2005, the majority of countries have limitations
5804 in providing a complete and accurate estimation of GHG emissions and removals from
5805 forest land. Some gaps in the current monitoring capacities can be summarized by
5806 considering the five IPCC GPG estimation and reporting principles:

5807

- 5808 • **Consistency:** Reporting by many countries are based either on single-date
5809 measurements or on integrating different heterogeneous data sources rather than
5810 using a systematic and consistent monitoring;
- 5811 • **Transparency:** Expert opinions, independent assessments or model estimations
5812 are commonly used as information source for forest carbon data (Holmgren et al.
5813 2007); often causing a lack of transparency in the methods used;
- 5814 • **Comparability:** Few countries have experience in using the IPCC GPG as
5815 common estimation and reporting format among Parties;
- 5816 • **Completeness:** The lack of suitable forest resource data in many non-Annex
5817 countries is evident for both area change and changes carbon stocks. Carbon
5818 stock data for aboveground and belowground carbon are often based on
5819 estimations or conversions using IPCC default data and very few countries are
5820 able to provide information on all five carbon pools.
- 5821 • **Accuracy:** There is limited information on error sources and uncertainties of the
5822 estimates and reliability levels by countries and approaches to analyze, reduce,
5823 and deal with them for international reporting and for implementation of carbon
5824 crediting procedures.

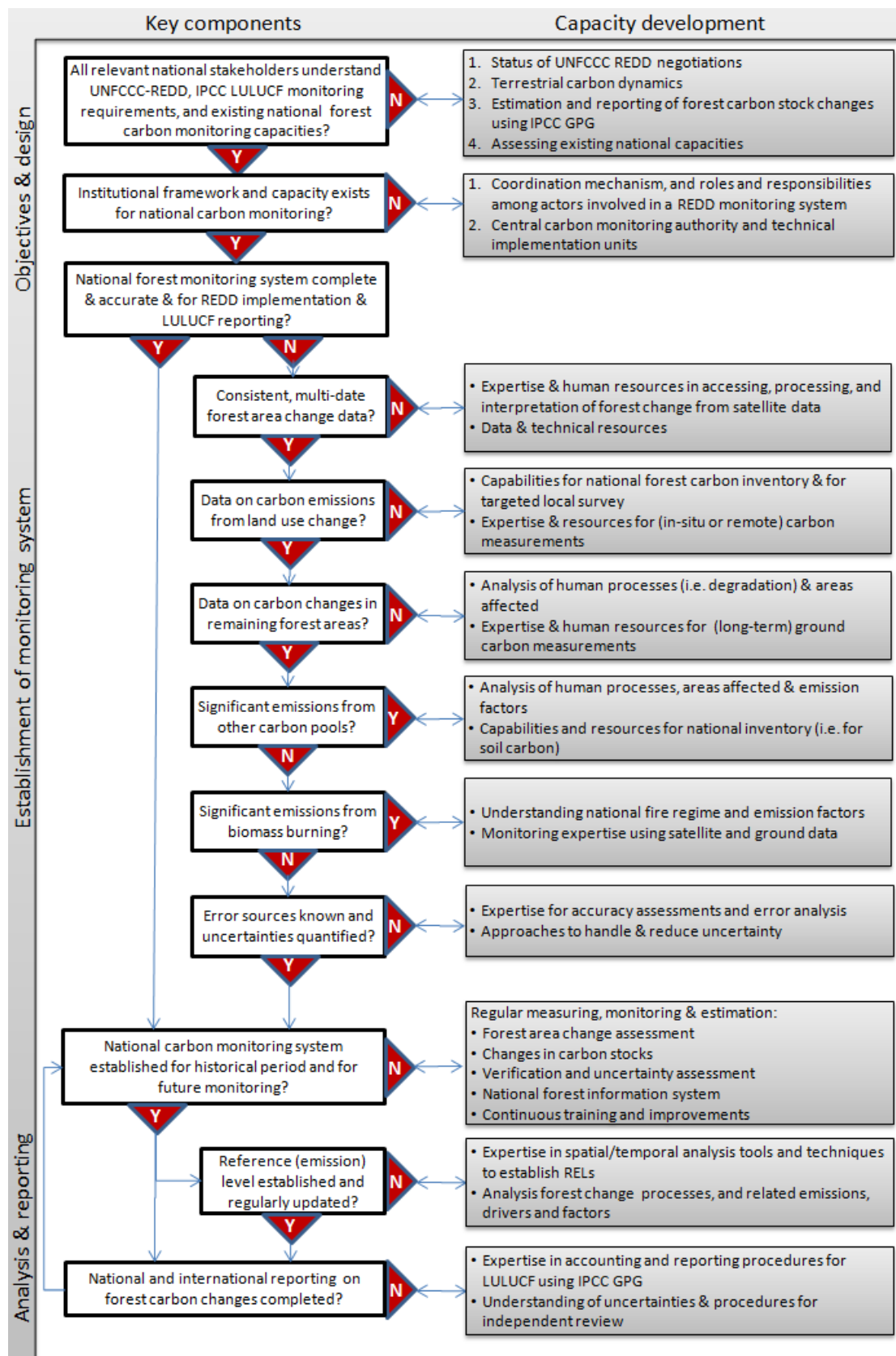
5825 **3.5.2.3 Key elements and required capacities**

5826 The pathways and cost implications for countries to establish REDD monitoring system
5827 requires understanding of the capacity gap between what is needed for such a system
5828 (see Table 3.5.1) and the status of current monitoring capacities. The important steps to
5829 be considered by countries are outlined in Figure 3.5.4. Fundamental to this is
5830 understanding of all relevant national actors about the international UNFCCC decisions
5831 and SBSTA guidance on REDD, the status of the national REDD implementation
5832 activities, knowledge of IPCC LULUCF good practice guidelines and expertise in terrestrial
5833 carbon dynamics and related human-induced changes.

5834

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Figure 3.5.4: Flowchart for the process to establishing a national monitoring system linking key components and required capacities (see Table 3.5.1).



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Uncertain input data (i.e. on forest area change and C stock change) is a common phenomenon among non-Annex I countries but adequate methods exist to improve

5841 monitoring capacities. A starting point is to critically analyze existing forest data and
 5842 monitoring capacities for the purpose of systematic estimation and reporting using the
 5843 IPCC LULUCF GPG. Table 3.5.2 lists several key existing data sources that are commonly
 5844 considered useful.

5845

5846 **Table 3.5.2: Examples of important existing data sources useful for establishing**
 5847 **national REDD monitoring**

Variable	Focus	Existing records	Existing information
Area changes (activity data)	Deforestation	Archived satellite data & airphotos Field surveys and forest cover maps	Maps & rates of deforestation and /or forest regrowth
	Forest regrowth	Maps of forest use and human infrastructures	Land use change maps National statistical data
Changes in carbon stocks / emission factors	Land use change (deforestation)	Forest inventory, site measurements Permanent sample plots, research sites	Carbon stock change and emission/ha estimates
	Changes in areas remaining forests	Forest/ecosystem stratifications Forest concessions/harvest estimates	Long-term measurements of human induced carbon stock changes
	Different C-pools (i.e. soils)	Volume to carbon conversion factors Regional carbon stock data/maps	
Biomass burning	Emissions of several GHG	Records of fire events (in-situ) Satellite data Emission factor measurements Records of areas under slash and burn cultivation	Burnt area map products Fire regime, area, frequency & emissions
Ancillary (spatial) data	Drivers & factors of forest changes	Topographic maps Field surveys Census data	GIS-datasets on population, roads, land use, planning, topography, settlements

5848

5849 The assessment of existing and required capacities should independently consider the
 5850 different IPCC variables. In case there are no consistent times series of historical forest
 5851 area change data, the country should consider using archived satellite data and establish
 5852 the required monitoring capacities. Forest inventory data are currently the most common
 5853 data source for the estimation of changes in forest carbon stocks. However most of the
 5854 existing and traditional forest inventories have not been designed for carbon stock
 5855 assessments and have limited use for this purpose. Ideally and in some contrast to
 5856 traditional inventories, the design for national carbon stock inventory should consider the
 5857 following requirements:

5858 • **Stratification** of forest area: by carbon density classes and relevant human
 5859 activities effecting forest carbon stocks;

5860 • **Coverage:** full national coverage with most detail and accuracy required in areas
 5861 of "REDD relevant activities";

5862 • **Site measurements:** emphasize on measuring carbon stocks, potentially in all
 5863 carbon pools;

5864 • **Time:** consistent and recurring measurements of carbon stock change, i.e. for
 5865 deforestation and in areas remaining as forests (i.e. degradation);

5866 • **Uncertainties:** verification and considerations for independent international
5867 review.

5868

5869 The investments and priority setting for monitoring carbon stock changes related to
5870 forests, in all carbon pools (i.e. soils, biomass burning) may depend on how significant
5871 the related human-induced changes are for the overall carbon budget and the national
5872 REDD implementation strategy are. For example, if the country has no fire regime and
5873 no significant emission from biomass burning it is not necessary to develop a related
5874 monitoring. The monitoring of carbon changes in forests remaining as forests (both
5875 increase and decrease) is generally less efficient than for the case deforestation, i.e.
5876 lower carbon stock changes per ha versus higher monitoring costs and, usually, lower
5877 accuracies. On the other hand, monitoring of forest degradation is important since the
5878 cumulative emission can be significant and updated data are required to avoid
5879 displacement of emissions from reduced deforestation. A country should have
5880 understanding and regularly monitor the human processes causing loss or increases in
5881 forest carbon stocks, i.e. through a recurring assessment of degraded forest area.
5882 However, the level of detail and accuracy for actual carbon stock changes should be
5883 higher for countries interested in claiming credits for their activities (i.e. reducing
5884 emissions from forest degradation). In this case, the establishing the REDD monitoring
5885 system should put particular emphasis in building the required capacities that usually
5886 require long-term, ground-based measurements. A similar procedure maybe suggested
5887 for the monitoring of changes in other carbon pools. To date, very few developing
5888 countries report data on soil carbon, even though emissions maybe significant, i.e.
5889 emissions from deforested or degraded peatlands. If the soil carbon pool is to be
5890 included in country strategy to receive credits for reducing emissions from forest land,
5891 the related monitoring component should be established from the beginning to provide
5892 the required accuracy for estimation and reporting. For other countries, the monitoring
5893 of emissions and removals from all carbon pools and all categories is certainly
5894 encouraged in the longer-term but maybe of lower priority and require smaller amount
5895 of resources in the readiness phase. This approach is supported the current IPCC
5896 guidance which already allow a cost-efficient use of available resources, e.g. the concept
5897 of key categories⁵⁶ indicate that priority should be given to the most relevant categories
5898 and/or carbon pools. This flexibility can be further expanded by the concept of
5899 conservativeness⁵⁷.

5900

5901 The analysis and use of existing data is most important for the estimation of historical
5902 changes and for the establishment of the reference emission levels. Limitations of
5903 existing data and information may constrain the accuracy and completeness of the
5904 LULUCF inventory for historical periods, i.e. for lack of ground data. In case of uncertain
5905 or incomplete data, the estimates should follow, as much as possible, the IPCC reporting
5906 principles and should be treated conservatively with motivation to improve the
5907 monitoring over time. The monitoring and estimation activities for the historical period
5908 should include a process for building the required capacities within the country to
5909 establish the monitoring, estimation and reporting procedures as long-term term system.
5910 Consistency between the estimates for the historical period and future monitoring is

⁵⁶ Key categories are sources of emissions/removals that contribute substantially to the overall national inventory (in terms of absolute level and/or trend). According to the IPCC-GPG, key categories should be estimated higher Tiers (2 or 3), which means that Tier 1 is allowed for non-key categories.

⁵⁷ Conservativeness is a concept used by the provisions of the Kyoto Protocol (UNFCCC 2006). In the REDD context, conservativeness may mean that - when completeness or accuracy of estimates cannot be achieved - the reduction of emissions should not be overestimated, or at least the risk of overestimation should be minimized (see section 4)

5911 essential. The existing gaps and known uncertainties of the historical data should be
5912 addressed in future monitoring efforts as part of a continuous improvement and training
5913 program.

5914

5915 **3.5.3 Capacity gaps and cost implications**

5916 There are several categories of costs to be considered for countries to engage in REDD
5917 including opportunity costs, and costs for transactions and implementation. Monitoring,
5918 reporting and verification of forest carbon are primarily reflected in the transaction costs,
5919 i.e. proof that a REDD activity has indeed achieved a certain amount of emission
5920 reductions and is suitable for compensation. The resources needed for monitoring are
5921 one smaller component considering all cost factors for REDD implementation in the long-
5922 term, but are rather significant in the readiness phase since many countries require the
5923 development of basic capacities.

5924

5925 Estimating the costs for REDD monitoring has to consider several issues that depend on
5926 the specific country circumstances. First, there is a difference in the cost structure for
5927 developing and establishing a monitoring system versus the operational implementation.
5928 For countries starting with limited capabilities significantly larger amount of resources
5929 are anticipated, particularly for monitoring historical forest changes and for the
5930 establishment reference emissions levels and near term monitoring efforts. In some
5931 cases it is assumed that readiness costs require significant public investment and
5932 international support, while all implementation costs (including the verification of
5933 compliance) should be ideally covered by carbon revenues (Hoare et al., 2008).
5934 Secondly, different components of the monitoring system, i.e. forest area change
5935 monitoring and measurements of carbon stock change have different cost implications
5936 depending on what method is used and which accuracy is to be achieved. For example,
5937 an annual forest area change monitoring combined with Tier 3 carbon stock change
5938 maybe more costly but less accurate than using 5-year intervals for monitoring forest
5939 area and carbon stock change on Tier 2 level.

5940

5941 Specific information on the costs for REDD are rare but experiences of estimates in this
5942 section is based on a number of resources:

- 5943 • Operational national forest monitoring examples (i.e. from India and Brazil)
- 5944 • Ongoing forest monitoring programs involving developing countries ranging from
5945 local case studies to global assessment programs (i.e. from FAO activities)
- 5946 • Idea notes and proposals submitted by countries to the Worldbank Forest Carbon
5947 Partnership Facility (FCPF)
- 5948 • Scientific literature documented in REDD-related monitoring and case studies
- 5949 • Expert estimates and considerations documented in reports (i.e. consultant
5950 reports) and international organizations and panels.

5951

5952 There are number of lump sum cost predictions for REDD monitoring. For example,
5953 Hoare et al. (2008) estimate between 1-6 Mill US\$ for the establishment of the REL and
5954 the monitoring system per country. This assessment is largely based on work by
5955 Hardcastle et al. (2008) that estimate cost for monitoring for different country
5956 circumstances building on knowledge of existing capacities. Operational monitoring costs
5957 are often provided as per area unit numbers (i.e. see examples from India and Brazil).
5958 Building upon these efforts, the aim of the following section is not provide specific
5959 number since they largely vary based on country circumstances and REDD objectives.

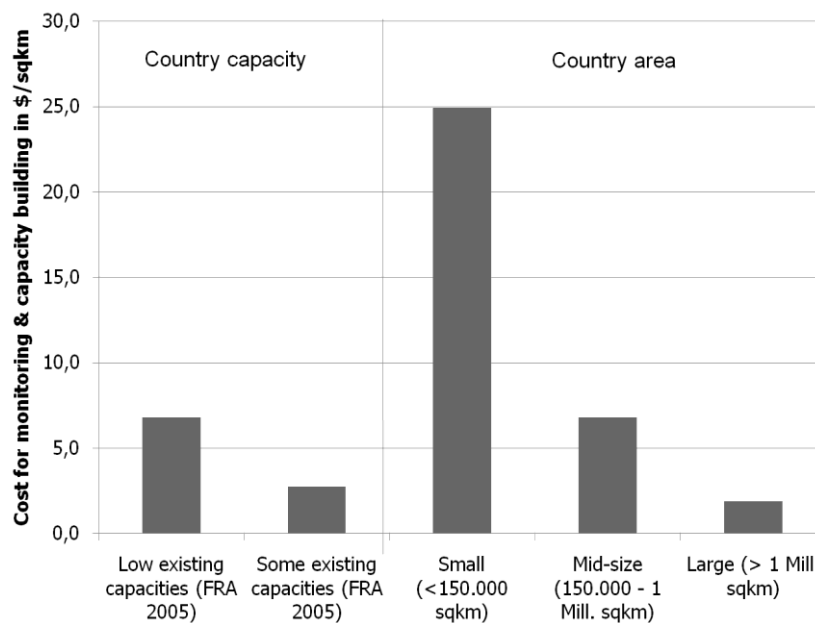
5960 **3.5.3.1 Importance of monitoring for establishing a national REDD**
 5961 **infrastructure**

5962 Costs for monitoring and technical capacity development will be an important component
 5963 in the REDD readiness phase. Understanding the historical forest change processes is
 5964 fundamental for the developing a national REDD strategy based on current forest and
 5965 environmental legislation. Establishing a national reference scenario for emissions from
 5966 deforestation and forest degradation based on available historical data is an initial
 5967 requirement. This effort involves capacity development to establish a sustained national
 5968 system for monitoring, reporting, and verifying emissions and removals from forest land
 5969 in the long-term.

5970

5971 The distribution of costs for monitoring activities (done by the country itself or with help
 5972 from international partners), and costs for capacity development are related to the
 5973 existing country capacities and country size. Figure 3.5.5 shows an assessment of 15
 5974 Readiness Plan Idea Notes (R-Pins) submitted to the Worldbank Forest Carbon
 5975 Partnership Facility that have provided budget details. The combined cost of monitoring
 5976 and capacity building activities range from 2-25 US\$ per sqkm depending on the land
 5977 area and existing capabilities. Countries with low existing capacity indicated more
 5978 required resources, with a larger proportion towards capacity building. The monitoring
 5979 efficiency for small countries is usually challenged since an initial amount of base
 5980 investments are equally required for all country sizes, i.e. a minimum standard for
 5981 operational institutional capacities, technical and human resources, and expertise in
 5982 reporting.

5983 **Figure 3.5.5:** Indicative costs per sqkm for monitoring and capacity building as part of
 5984 the proposed Worldbank FCPF readiness activities. The graph shows median values
 5985 based on 15 R-PIN's separated by country capacities and land area. Countries were
 5986 considered to have low capacities if they did not report either forest area change based
 5987 on multi-date data or data on forest carbon stocks for the last FAO FRA (FAO, 2006).



5988

5989 **3.5.3.2 Planning and design**

5990 Planning and design activities should result in a national REDD monitoring framework
 5991 (incl. definitions, monitoring variables, institutional setting etc.), and a plan for capacity
 5992 development and long-term improvement and the estimation anticipated costs.
 5993 Fundamental for this process is the understanding of relevant national actors about the
 5994 international UNFCCC negotiations on REDD, the status of the national REDD

5995 implementation activities, knowledge in the application of IPCC LULUCF good practice
5996 guidelines and expertise in terrestrial carbon dynamics and related human-induced
5997 changes. Resources for related training and capacity building are required to participate
5998 in or organize dedicated national or regional workshops or to hire international
5999 consultants or experts. Some initiatives are already offering capacity development
6000 workshops to countries for this purpose, i.e. as part of GTZ's CD-REDD program
6001 ([http://unfccc.int/files/methods_science/redd/technical_assistance/training_activities/ap
6002 plication/pdf/cd_redd_concept_note.pdf](http://unfccc.int/files/methods_science/redd/technical_assistance/training_activities/application/pdf/cd_redd_concept_note.pdf)).

6003 **3.5.3.3 Institutional capacities**

6004 A suitable degree of organizational capacity within the country is required to establish
6005 and operate a national forest carbon monitoring program. Activities include acquisition of
6006 different types of data, analysis, estimation, international reporting, and the use of forest
6007 data to support REDDS implementation. Different actors and sectors are to be working in
6008 coordination to make a REDD monitoring system efficient in the long-term. As a
6009 minimum, a country should consider maintaining the following institutions with clear
6010 definition of roles and responsibilities:

- 6011 • National REDD coordination and steering body or advisory board
- 6012 • Central carbon monitoring, estimation and reporting authority
- 6013 • Forest carbon monitoring implementation units

6014

6015 The size and amount of resources required for setting up and maintaining institutional
6016 capacities depend on several factors. Some countries will perform most of the
6017 acquisition, processing, and analysis of data by their agencies or centralized units;
6018 others may decide to build upon outside partners (i.e. contractors, local communities or
6019 regional centers). Although a minimum amount of institutional capacities is required
6020 even for small countries, larger countries will need to invest in a more complex and more
6021 expensive organisation structure.

6022 **3.5.3.4 Cost factors for monitoring change in forest area**

6023 Fundamental requirements of national monitoring systems are that they measure
6024 changes throughout all forested area, use consistent methodologies at repeated intervals
6025 to obtain accurate results, and verify results with ground-based or very high quality
6026 observations. The only practical approach for such monitoring systems is through
6027 interpretation of remotely sensed data supported by ground-based observations. The use
6028 field survey and inventory type data for national level estimation of activity is performed
6029 by several Annex I countries (Achard et al., 2008). However, the use of satellite remote
6030 sensing observations (in combination field observations for calibration and validation) for
6031 consistent and efficient monitoring of forest area change using Approach 3 if the IPCC
6032 GPG can be assumed to be the most common option for REDD activities in developing
6033 countries; in particular for countries with limited information for the historical period.

6034

6035 The implementation of the satellite-based monitoring system includes a number of cost
6036 factors:

- 6037 1. Satellite data incl. data access and processing
- 6038 2. Soft/Hardware and office resources (incl. satellite data archive)
- 6039 3. Human resources for data interpretation and analysis
 - 6040 a. Monitoring in readiness phase
 - 6041 b. Operational monitoring
- 6042 4. Accuracy assessment

6043 5. Regional cooperation

6044

6045 For countries without existing operational capacities the costs for developing the
6046 required human capacities required will need to be considered. In the establishment
6047 phase, the work of both national and international experts include the following
6048 activities:

- 6049 a) Assessment and best use of existing observations and information;
- 6050 b) Specify a methodology and operational implementation framework for
6051 monitoring forest area change on a national level;
- 6052 c) Perform analysis of historical satellite data for establishing reference emission
6053 levels or reference levels;
- 6054 d) Develop understanding of areas affected by forest degradation and provide
6055 assessment on how to monitor relevant forest degradation processes;
- 6056 e) If required, set up system for real-time deforestation monitoring (i.e. including
6057 detection of forest fires and areas burnt);
- 6058 f) Complete recruitment and provide training to national team to perform
6059 monitoring activities;
- 6060 g) Complete an accuracy and error analysis for estimates from the historical
6061 period;
- 6062 h) Perform a test run of the operational forest area change monitoring system.

6063

6064 Once a monitoring system is consolidated in the readiness phase, the continuous
6065 monitoring operation produces annual operational costs for the different components of
6066 the system mentioned in Table 3.5.1. For example, if a country decides to monitor
6067 forest area change using its own resources and capacities the annual cost for human
6068 resources maybe on the order 3 to 4 times smaller than for the establishment phase
6069 (Hardcastle et al. 2008).

6070

6071 The resources required for operational monitoring depend on the size of the area to be
6072 mapped each year and the thematic detail and accuracy to be provided. In general, the
6073 smallest implementation unit of three skilled technicians should be sufficient to perform
6074 all operations for the consistent and transparent monitoring of forest area change for
6075 small to medium country sizes in 2- to 3-year time intervals. Costs for data and human
6076 resources will increase if an annual forest area change monitoring interval is performed.

6077 **3.5.3.5 Cost factors for monitoring change in carbon stocks**

6078 Estimates of carbon stocks in aboveground biomass of trees are frequently obtained by
6079 countries from various sources (Table 3.5.4), and for other forest carbon pools default
6080 data (for use with Tier 1 approach) provided by in the IPCC good practice guidance for
6081 LULUCF are normally used.

6082 Growing stock volume collected in conventional forest inventories can be used to
6083 produce biomass values using methods in the IPCC good practice guidance for LULUCF or
6084 other more specific methods proposed by some authors in line with them. The
6085 stratification by forest types and management practices, for example, mature forest,
6086 intensely logged, selectively logged, fallow, could help to achieve more accurate and
6087 precise results. Many developing countries use some country-specific inventory data to
6088 estimate carbon stocks of forests (but often, they use factors from the IPCC to convert
6089 volume to biomass); this could be seen to be equivalent to a low level Tier 2 for emission
6090 factors as defined in the IPCC good practice guidance for LULUCF.

6091 However, conventional forest inventories are often done in forests deemed to be
6092 productive for timber harvesting, often do not include forests that have little commercial
6093 timber, and measurements may have not been stratified and acquired for carbon stock
6094 assessments. Also, as Table 3.5.4 shows, many inventories are old and out of date and
6095 may not be the forests undergoing deforestation.

6096 Compilation of data from ecological or other permanent sample plots may provide
6097 estimates of carbon stocks for different forest types but are subject to the design of
6098 particular scientific studies and thus tend to produce unreliable estimates over large
6099 forest areas.

6100

6101 Before initiating a program to monitor carbon stocks of land cover classes, certain
6102 decisions will need to be made concerning the following key factors that directly impact
6103 the cost of implementing a monitoring system:

6104 i) What level of accuracy and precision is to be attained—the higher the targeted
6105 accuracy and precision (or lower uncertainty) of estimates of carbon stocks
6106 the higher the cost to monitor;

6107 j) How to stratify forest lands—stratification into relatively homogeneous units of
6108 land with respect to carbon stocks lowers the cost as it reduces the number of
6109 sample plots;

6110 k) Which carbon pools to include—the more carbon pools included the higher the
6111 cost; and

6112 l) At what time intervals should carbon stocks in specific areas be monitored
6113 over time; the shorter the time interval, the higher the cost and specific areas
6114 targeted for REDD implementation activities may require more frequent
6115 measurements

6116 For estimation of carbon stocks on the land, there is a need for sampling rather than
6117 attempt to measure everything noting that sampling is the process by which a subset is
6118 studied to allow generalizations to be made about the whole population or area of
6119 interest. The values attained from measuring a sample are an estimation of the
6120 equivalent value for the entire area or population. Statistics provide us with some idea
6121 of how close the estimation is to reality and therefore how certain or uncertain the
6122 estimates are.

6123

6124 The accuracy and precision of ground-based measurements depend on the methods
6125 employed and the frequency of collection. If insufficient measurement effort is
6126 expended, then the results will most likely be imprecise. In addition, estimates can be
6127 affected by sampling errors, assessment errors, classification errors in remote sensing
6128 imagery and model errors that propagate through to the final estimation.

6129 Total monitoring costs are dependent on a number of fixed and variable costs. Costs
6130 that vary with the number of samples taken are variable costs, for example, labor is a
6131 variable cost because expenditure on labor varies with the number of sample plots
6132 required. Fixed costs do not vary with the number of sample plots taken. The total cost
6133 of a single measurement event is the sum of variable and fixed costs.

6134 There are several variable costs associated to ground based sampling in forest that could
6135 include or depend on:

6136 a) Labor required which depends on sampling size;

6137 b) Equipment use and rental;

6138 c) Communication equipment use and rental;

6139 d) Food and accommodation;

6140 e) Field supplies for collecting field data;

6141 f) Transportation and analysis costs of any field samples (e.g. drying biomass
6142 samples).

6143 Variable costs listed in categories (a) to (d) in paragraph above will vary with the
6144 number of samples required; the time taken to collect each sample and the time needed
6145 to travel from one sample site to another (e.g. affected by the size and spatial
6146 distribution of the area being contiguous or non-contiguous), as well as, by the number
6147 of forest carbon pools required. These are the major factors expected to influence
6148 overall sampling time. At a national scale, it is likely that travel time between plots
6149 could be as long as or longer than the actual time to collect all measurements in a plot.
6150 Costs listed in sub-bullets (e) and (f) are only dependent on the number of samples
6151 required.

6152 The cost for deriving estimates of forest carbon stocks based on field measurements and
6153 sampling depends on the targeted precision level. The higher the level of precision the
6154 more plots are needed, similar precision may require more or less samples depending on
6155 the variability of the carbon stocks in the plot. A measure of the variability commonly
6156 used is the coefficient of variation of the carbon stock estimates, the higher the
6157 coefficient of variation the more variable the stocks and the more plots needed to
6158 achieve the same level of precision.

6159 Stratification of forest cover can increase the accuracy and precision of the measuring
6160 and monitoring in a cost-effective manner (see [section 2.2](#)). Carbon stocks may vary
6161 substantially among forest types depending on physical factors (e.g., climate types,
6162 precipitation regime, temperature, soil type, and topography), biological factors (tree
6163 species composition, stand age, stand density) and anthropogenic factors (e.g.
6164 disturbance history and logging intensity).

6165 **3.5.3.6 Spatial data infrastructure, access and reporting procedures**

6166 A centralized spatial data infrastructure should be established to gather, store, archive,
6167 and analyze all required data for the national reporting. This requires resources to
6168 establish and maintain a centralized database and information system integrating all
6169 required information for LULUCF. There is need to establish a data infrastructure, incl.
6170 information technology (suitable hard/software), and for human resources to generate,
6171 manipulate, apply, and interpret the data, as well as capability to perform the reporting
6172 and accounting using the UNFCCC guidelines, and meet the international reporting
6173 obligations. There should also be consideration of data access procedures for (spatially
6174 explicit) information in transparent form.

6175 **3.5.4 Key references for section 3.5**

6176

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6201

6202

6203

6204

6205 **4 GUIDANCE ON REPORTING**

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6210

6211 **4.1 SCOPE OF CHAPTER**

6212 **4.1.1 The importance of good reporting**

6213 Under the UNFCCC, information reported in greenhouse gas (GHG) inventories
6214 represents an essential link between science and policy, providing the means by which
6215 the COP can monitor progress made by Parties in meeting their commitments and in
6216 achieving the Convention's ultimate objectives. In any international system in which an
6217 accounting procedure is foreseen - as in the Kyoto Protocol and likely also in a future
6218 REDD mechanism - the information reported in a Party's GHG inventory represents the
6219 basis for assessing each Party's performance as compared to its commitments or
6220 reference scenario, and therefore represents the basis for assigning eventual incentives
6221 or penalties.

6222 The quality of GHG inventories relies not only upon the robustness of the science
6223 underpinning the methodologies and the associated credibility of the estimates - but also
6224 on the way this information is compiled and presented. Information must be well
6225 documented, transparent and consistent with the reporting requirements outlined in the
6226 UNFCCC guidelines.

6227 **4.1.2 Overview of the Chapter**

6228 **Section 4.2** gives an overview of the current reporting requirements under UNFCCC,
6229 including the general underlying principles. The typical structure of a GHG inventory is
6230 illustrated, including an example table for reporting C stock changes from deforestation.

6231 **Section 4.3** outlines the major challenges that developing countries will likely encounter
6232 when implementing the reporting principles described in section 4.2.

6233 **Section 4.4** elaborates concepts already agreed upon in a UNFCCC context and
6234 describes how a conservative approach may help to overcome some of the difficulties
6235 described in Section 4.3.

6236

6237 **4.2 OVERVIEW OF REPORTING PRINCIPLES AND** 6238 **PROCEDURES**

6239 **4.2.1 Current reporting requirements under the UNFCCC**

6240 Under the UNFCCC, all Parties are required to provide national inventories of
6241 anthropogenic emissions by sources and removals by sinks of all greenhouse gases not

6242 controlled by the Montreal Protocol. To promote the provision of credible and consistent
6243 GHG information, the COP has developed specific reporting guidelines that detail
6244 standardized requirements. Although these requirements differ across Parties, they are
6245 similar in that they are based on IPCC methodologies and aim to produce a full,
6246 accurate, transparent, consistent and comparable reporting of GHG emissions and
6247 removals.

6248 At present, detailed reporting guidelines exist for the annual GHG inventories of Annex I
6249 Parties (UNFCCC 2004)⁵⁸, while only generic guidance is available for the preparation of
6250 national communications from non-Annex I Parties⁵⁹. This difference reflects the fact that
6251 Annex I (AI) Parties are required to report detailed data on an annual basis that are
6252 subject to in-depth review by teams of independent experts, while Non-Annex I Parties
6253 (NAI) currently report less often and in less detail. As a result, their national
6254 communications are not subject to in-depth reviews.

6255 However, given the potential relevance of a future REDD mechanism - and the
6256 consequent need for robust and defensible estimates - the reporting requirements of NAI
6257 Parties on emissions from deforestation will certainly become more stringent and may
6258 come close to the level of detail currently required from AI Parties. This tendency is
6259 confirmed by recent documents agreed during REDD negotiations - i.e. the
6260 demonstration REDD activities should produce estimates that are "*results based,*
6261 *demonstrable, transparent, and verifiable, and estimated consistently over time*"⁶⁰.
6262 Therefore, although at present it is not possible to foresee the exact reporting
6263 requirements of a future REDD mechanism, they will likely follow the general principles
6264 and procedures currently valid for AI parties and outlined in the following section.

6265 **4.2.2 Inventory and reporting principles**

6266 Under the UNFCCC, there are five general principles which should guide the estimation
6267 and the reporting of emissions and removals of GHGs: Transparency, Consistency
6268 Comparability Completeness and Accuracy. Although some of these principles have been
6269 already discussed in previous chapters, below are summarized and their relevance for
6270 the reporting is highlighted:

6271 • *Transparency*, i.e. all the assumptions and the methodologies used in the
6272 inventory should be clearly explained and appropriately documented, so that anybody
6273 could verify its correctness.

6274 • *Consistency*, i.e. the same definitions and methodologies should be used along
6275 time. This should ensure that differences between years and categories reflect real
6276 differences in emissions. Under certain circumstances, estimates using different
6277 methodologies for different years can be considered consistent if they have been
6278 calculated in a transparent manner. Recalculations of previously submitted estimates are
6279 possible to improve accuracy and/or completeness, providing that all the relevant
6280 information is properly documented. In a REDD context, consistency also means that all
6281 the lands and all the carbon pools which have been reported in the reference period
6282 must to be tracked in the future (in the Kyoto language it is said "once in, always in").
6283 Similarly, the inclusion of new sources or sinks which have existed since the reference

⁵⁸ UNFCCC 2004 Guidelines for the preparation of national communications by Parties included in Annex I to the Convention, Part I: UNFCCC reporting guidelines on annual inventories (FCCC/SBSTA/2004/8).

⁵⁹ UNFCCC 2002 Guidelines for the preparation of national communications from Parties not included in Annex I to the Convention (FCCC/CP/2002/7/Add.2).

⁶⁰ Decision -/CP.13. http://unfccc.int/files/meetings/cop_13/application/pdf/cp_redd.pdf.

6284 period but were not previously reported (e.g., a carbon pool), should be reported for the
6285 reference period and all subsequent years for which a reporting is required.

6286 • *Comparability* across countries. For this purpose, Parties should follow the
6287 methodologies and standard formats (including the allocation of different source/sink
6288 category) provided by the IPCC and agreed within the UNFCCC for estimating and
6289 reporting inventories (see also chapter 2.1). It shall be noted that the comparability
6290 principle may be extended also to definitions (e.g. definition of forest) and estimates
6291 (e.g. forest area, average C stock) provided by the same Party to different international
6292 organizations (e.g. UNFCCC, FAO). In that case, any discrepancy should be adequately
6293 justified.

6294 • *Completeness*, meaning that estimates should include – for all the relevant
6295 geographical coverage – all the agreed categories, gases and pools. When gaps exist, all
6296 the relevant information and justification on these gaps should be documented in a
6297 transparent manner.

6298 • *Accuracy*, in the sense that estimates should be systematically neither over nor
6299 under the true value, so far as can be judged, and that uncertainties are reduced so far
6300 as is practicable. Appropriate methodologies should be used, in accordance with the
6301 IPCC, to promote accuracy in inventories and to quantify the uncertainties in order to
6302 improve future inventories.

6303 Furthermore, these principles also guide the process of independent review of all the
6304 GHG inventories submitted by AI Parties to the UNFCCC.

6305 **4.2.3 Structure of a GHG inventory**

6306 A national inventory of GHG anthropogenic emissions and removals is typically divided
6307 into two parts:

6308 **Reporting Tables** are a series of standardized data tables that contain mainly
6309 quantitative (numerical) information. Box 4.2.1 shows an example table for reporting C
6310 stock changes following deforestation (modified from Kyoto Protocol LULUCF tables for
6311 illustrative purposes only). Typically, these tables include columns for:

6312 - *The initial and final land-use category*. Additional stratification is encouraged (in a
6313 separate column for subcategories) according to criteria such as climate zone,
6314 management system, soil type, vegetation type, tree species, ecological zones, national
6315 land classification or other factors.

6316 - The "*activity data*", i.e., area of land (in thousands of ha) subject to gross deforestation
6317 and degradation (see Section 2.1)

6318 - The "*emission factors*", i.e., the C stock changes per unit area deforested or degraded,
6319 separated for each carbon pool (see Sections 2.2 & 2.3). The term "implied factors"
6320 means that the reported values represent an average within the reported category or
6321 subcategory, and serves mainly for comparative purposes.

6322 - *The total change in C stock*, obtained by multiplying each activity data by the relevant
6323 emission C stock change factor.

6324 - *the total emissions* (expressed as CO₂).

6325

Box 4.2.1: Example of a typical reporting table

for reporting C stock changes following deforestation.

GREENHOUSE GAS SOURCE AND SINK CATEGORIES		ACTIVITY DATA	IMPLIED STOCK FACTORS ⁽²⁾						CARBON CHANGE	CHANGE IN CARBON STOCK ⁽²⁾						
			carbon stock change per unit area in:							carbon stock change in:						
Land-Use Category	Sub-division ⁽¹⁾	Total area (kha)	biomass		dead organic matter		soils	Implied emission factor per area ⁽³⁾	Biomass		dead organic matter		soils	Total CO ₂ emissions ⁽³⁾		
			above-ground	below-ground	above-ground	below-ground			above-ground	below-ground	above-ground	below-ground				
			(Mg C/ha)						(Mg CO ₂ /ha)	(Gg C)						(Gg CO ₂)
A. Total Deforestation																
1. Forest Land converted to Cropland	(specify)															
	(specify)															
2. Forest Land converted to Grassland	(specify)															
	(specify)															
.....																

(1) Land categories may be further divided according to climate zone, management system, soil type, vegetation type, tree species, ecological zones, national land classification or other criteria.

(2) The signs for estimates of increases in carbon stocks are positive (+) and of decreases in carbon stocks are negative (-).

(3) According to IPCC Guidelines, changes in carbon stocks are converted to CO₂ by multiplying C by 44/12 and changing the sign for net CO₂ removals to be negative (-) and for net CO₂ emissions to be positive (+).

Documentation box:

Use this documentation box to provide references to relevant sections of the Inventory Report if any additional information and/or further details are needed to understand the content of this table.

6327 To ensure the completeness of an inventory, it is good practice to fill in information for
 6328 all entries of the table. If actual emission and removal quantities have not been
 6329 estimated or cannot otherwise be reported in the tables, the inventory compiler should
 6330 use the following qualitative "notation keys" (from IPCC 2006 GL) and provide
 6331 supporting documentation.

6332

Notation key	Explanation
NE (Not estimated)	Emissions and/or removals occur but have not been estimated or reported.
IE (Included elsewhere)	Emissions and/or removals for this activity or category are estimated but included elsewhere. In this case, where they are located should be indicated,
C (Confidential information)	Emissions and/or removals are aggregated and included elsewhere in the inventory because reporting at a disaggregated level could lead to the disclosure of confidential information.
NA (Not Applicable)	The activity or category exists but relevant emissions and removals are considered never to occur.
NO (Not Occurring)	An activity or process does not exist within a country.

6333 For example, if a country decides that a disproportionate amount of effort would be
 6334 required to collect data for a pool from a specific category that is not a key category (see
 6335 see Sections 2.2 & 2.3) in terms of the overall level and trend in national emission, then
 6336 the country should list all gases/pools excluded on these grounds, together with a
 6337 justification for exclusion, and use the notation key 'NE' in the reporting tables.

6338 Furthermore, the reporting tables are generally complemented by a documentation box
 6339 which should be used to provide references to relevant sections of the Inventory Report
 6340 if any additional information is needed.

6341 In addition to tables like those illustrated in Box 4.2.1, other typical tables to be filled in
 6342 a comprehensive GHG inventory include:

6343 Tables with emissions from other gases (e.g., CH₄ and N₂O from biomass burning), to
 6344 be expressed both in unit of mass and in CO₂ equivalent (using the Global Warming
 6345 Potential of each gas provided by the IPCC)

6346 Summary tables (with all the gases and all the emissions/removals)

6347 Tables with emission trends (covering data also from previous submissions)

6348 Tables for illustrating the results of the key category analysis, the completeness of the
 6349 reporting, and eventual recalculations.

6350 In the context of REDD, most of these types of tables will likely need to be completed for
 6351 the reference period and for the assessment period, although it is not yet clear if non-
 6352 CO₂ gases and all pools will be required.

6353

6354 **Inventory Report:** The other part of a national inventory is an Inventory Report that
 6355 contains comprehensive and transparent information about the inventory, including:

6356 An overview of trends for aggregated GHG emissions, by gas and by category.

6357 A description of the methodologies used in compiling the inventory, the assumptions, the
 6358 data sources and rationale for their selection, and an indication of the level of complexity

6359 (IPCC tiers) applied. In the context of REDD reporting, appropriate information on land-
6360 use definitions, land area representation and land-use databases are likely to be
6361 required.

6362 A description of the key categories, including information on the level of category
6363 disaggregation used and its rationale, the methodology used for identifying key
6364 categories, and if necessary, explanations for why the IPCC-recommended Tiers have
6365 not been applied.

6366 Information on uncertainties (i.e., methods used and underlying assumptions), time-
6367 series consistency, recalculations (with justification for providing new estimates), quality
6368 assurance and quality control procedures.

6369 A description of the institutional arrangements for inventory preparation.

6370 Information on planned improvements.

6371 Furthermore, all of the relevant inventory information should be compiled and archived,
6372 including all disaggregated emission factors, activity data and documentation on how
6373 these factors and data were generated and aggregated for reporting. This information
6374 should allow, inter alia, reconstruction of the inventory by the expert review teams.

6375

6376 **4.3 WHAT ARE THE MAJOR CHALLENGES FOR** 6377 **DEVELOPING COUNTRIES?**

6378 Although the inventory requirements for a REDD mechanism have not yet been
6379 designed, it is possible to foresee some of the major challenges that developing
6380 countries will encounter in estimating and reporting emissions from deforestation and
6381 forest degradation. In particular, what difficulties can be expected if the five principles
6382 outlined above are required for REDD reporting?

6383 While specific countries may encounter difficulties in meeting transparency, consistency
6384 and comparability principles, it is likely that most countries will be able to fulfill these
6385 principles reasonably well after adequate capacity building. In contrast, based on the
6386 current monitoring and reporting capabilities, the principles of completeness and
6387 accuracy will likely represent major challenges for most developing countries, especially
6388 for estimating emissions of the reference period.

6389 Achieving the *completeness* principle will clearly depend on the processes (e.g.
6390 deforestation, forest degradation) involved, the pools and gases that needed to be
6391 reported, and the forest-related definitions that are applied. For example, evidence from
6392 official reports (e.g., NAI national communications to UNFCCC⁶¹, FAO's FRA 2005⁶²)
6393 suggests that only a very small fraction of developing countries currently reports data on
6394 soil carbon, even though emissions from soils following deforestation are likely to be
6395 significant in many cases.

6396 If *accurate* estimates of emissions are to be reported, reliable methodologies are needed
6397 as well as a quantification of their uncertainties. For key categories and significant pools,
6398 this implies the application of higher tiers, i.e. having country-specific data on all the
6399 significant pools stratified by climate, forest, soil and conversion type at a fine to
6400 medium spatial scale. Although adequate methods exist (as outlined in the previous
6401 chapters of the sourcebook), and the capacity for monitoring emissions from
6402 deforestation is improving, in many developing countries accurate data on deforested

⁶¹ UNFCCC. 2005. Sixth compilation and synthesis of initial national communications from Parties not included in Annex I to the Convention. FCCC/SBI/2005/18/Add.2

⁶² Food and Agriculture Organization. 2006. Global Forest Resources Assessment.

6403 areas and carbon stocks are still scarce and allocating significant extra resources for
6404 monitoring may be difficult in the near future.

6405 In this context, how could the obstacle of potentially incomplete and highly uncertain
6406 REDD reporting be overcome?

6407

6408 **4.4 THE CONSERVATIVENESS APPROACH**

6409 To address the potential incompleteness and the uncertainties of REDD estimates, and
6410 thus to increase their credibility, it has been proposed to use the approach of
6411 "conservativeness". Although conservativeness is, strictly speaking, an accounting
6412 concept, its consideration during the estimation and reporting phases may help, for
6413 example, in allocating resources in a cost-effective way (e.g. see section 4.4.1).

6414 In the REDD context, conservativeness means that - when completeness or accuracy of
6415 estimates cannot be achieved - the reduction of emissions should not be overestimated,
6416 or at least the risk of overestimation should be minimized.

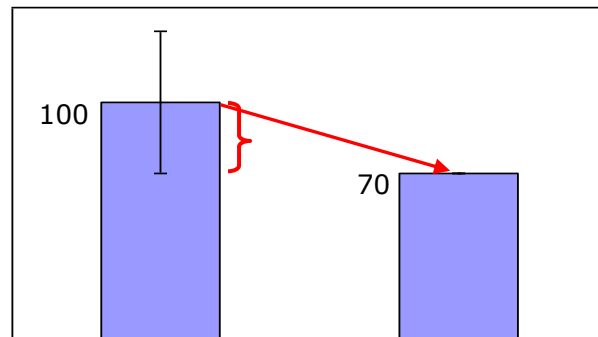
6417 Although this approach may appear new to some, it is already present in the UNFCCC
6418 context, even if somehow "hidden" in technical documents. For example, the procedure
6419 for adjustments under Art 5.2 of the Kyoto Protocol works as follows⁶³: if an AI Party
6420 reports to UNFCCC emissions or removals in a manner that is not consistent with IPCC
6421 methodologies and would give benefit for the Party, e.g. an overestimation of sinks or
6422 underestimation of emissions in a given year of the commitment period, then this would
6423 likely trigger an "adjustment", i.e., a change applied by an independent expert review
6424 team (ERT) to the Party's reported estimates. In this procedure, the ERT may first
6425 substitute the original estimate with a new one (generally based on a default IPCC
6426 estimate, i.e. a Tier 1) and then - given the high uncertainty of this new estimate -
6427 multiply it by a tabulated category-specific "conservativeness factor" (see Figure 4.4.1).
6428 Differences in conservativeness factors between categories reflect typical differences in
6429 total uncertainties, and thus conservativeness factors have a higher impact for
6430 categories or components that are expected to be more uncertain (based on the
6431 uncertainty ranges of IPCC default values or on expert judgment). In this way, the
6432 conservativeness factor acts to decrease the risk of underestimating emissions or
6433 overestimating removals in the commitment period. In the case of the base year, the
6434 opposite applies. In other words, the conservativeness factor may increase the "quality"
6435 of an estimate, e.g. decreasing the high "risk" of a Tier 1 estimate up to a level typical of
6436 a Tier 3 estimate. Of course, the extent of the correction depends also on the level of the
6437 confidence interval⁶⁴: for example, by taking the lower bound of the 50% or 95%
6438 confidence interval means, respectively, having 25% or 2.5% probability of
6439 overestimating the "true" value of the emissions (in case of Art. 5.2 of the Kyoto
6440 Protocol the 50% confidence interval is used). By contrast, by taking the mean value
6441 (and assuming a normal distribution) there is an equal chance (50%) for over- and
6442 under-estimation of the true value.

6443

⁶³ UNFCCC 2006. Good practice guidance and adjustments under Article 5, paragraph 2, of the Kyoto Protocol
FCCC/KP/CMP/2005/8/Add.3 Decision 20/CMP.1

⁶⁴ The confidence interval is a range that encloses the true (but unknown) value with a specified confidence
(probability). E.g., the 95 % confidence interval has a 95% probability of enclosing the true value.

6444 **Figure 4.4.1.** Conceptual example of the application of a conservativeness factor during
6445 the adjustment procedure under Art. 5.2 of the Kyoto Protocol. The bracket indicates the
6446 risk of overestimating the true value, which is high if, for example, a Tier 1 estimate is
6447 used. Multiplying this estimate by a conservativeness factor (in this case 0.7), derived
6448 from category-specific tabulated confidence intervals, means decreasing the risk of
6449 overestimating the true value.



6450

6451

6452 Another example comes from the modalities for afforestation and reforestation project
6453 activities under the Clean Development Mechanism (CDM)⁶⁵, which prescribes that “the
6454 baseline shall be established in a transparent and conservative manner regarding the
6455 choice of approaches, assumptions, methodologies, parameters, data sources, ...and
6456 taking into account uncertainty”.

6457 Furthermore, the concept of conservativeness is *implicitly* present also elsewhere. For
6458 example, the Marrakech Accords specify that, under Articles 3.3 and 3.4 of the Kyoto
6459 Protocol, Annex I Parties “may choose not to account for a given pool if transparent and
6460 verifiable information is provided that the pool is not a source”, which means applying
6461 conservativeness to an incomplete estimate. In addition, the IPCC GPG-LULUCF (2003)
6462 indicates the use of the Reliable Minimum Estimate (Chapter 4.3.3.4.1) as a tool to
6463 assess changes in soil carbon, which means applying conservativeness to an uncertain
6464 estimate.

6465 Very recently, this concept entered also in the text of ongoing REDD negotiations⁶⁶,
6466 where among the methodological issues identified for further consideration it was
6467 included “Means to deal with uncertainties in estimates aiming to ensure that reductions
6468 in emissions or increases in removals are not over-estimated”.

6469 However, although the usefulness of the conservativeness concept seems largely
6470 accepted, its application in the REDD context clearly needs some guidance. In other
6471 words: how to implement, in practice, the conservativeness approach to the REDD
6472 context? To this aim, the next two sections show some examples on how the
6473 conservativeness approach may be applied to a REDD mechanism when estimates are
6474 incomplete or uncertain, respectively.

6475

⁶⁵ UNFCCC 2006. Modalities and procedures for afforestation and reforestation project activities under the clean development mechanism in the first commitment period of the Kyoto Protocol Decision 5/CMP.1

⁶⁶ <http://unfccc.int/resource/docs/2008/sbsta/eng/l12.pdf>

6476 **4.4.1 Addressing incomplete estimates**

6477 It is likely that a typical and important example of incomplete estimates will arise from
 6478 the lack of reliable data for a carbon pool, and especially the soil pool. In this case, being
 6479 conservative in a REDD context does not mean “not overestimating the emissions”, but
 6480 rather “not overestimating the reduction of emissions”. If soil is not accounted for, the
 6481 total emissions from deforestation will very likely be underestimated in both periods.
 6482 However, assuming for the most disaggregated reported level (e.g., a forest type
 6483 converted to cropland) the same emission factor (C stock change/ha) in the two periods,
 6484 and provided that the area deforested is reduced from the reference to the assessment
 6485 period, also the reduced emissions will be underestimated. In other words, although
 6486 neglecting soil carbon will cause a REDD estimate which is not complete, this estimate
 6487 will be conservative (see Table 4.4.1) and therefore should not be considered a problem.
 6488 However, this assumption of conservative omission of a pool is *not* valid anymore if, for
 6489 a given forest conversion type, the area deforested is increased from the reference to
 6490 the assessment period; in such case, any pool which is a source should be estimated and
 6491 reported.

6492

6493 **Table 4.4.1:** Simplified example of how ignoring a carbon pool may produce a
 6494 conservative estimate of reduced emissions from deforestation. The reference level
 6495 might be assessed on the basis of historical emissions. (a) complete estimate, including
 6496 the soil pool; (b) incomplete estimate, as the soil pool is missing. The latter estimate of
 6497 reduced emissions is not accurate, but is conservative.

	Area deforest ed (ha x 10 ³)	Carbon stock change (t C/ha deforested)		Emissions (area deforested x C stock change, t C x 10 ³)	
		Above- ground Biomass	Soil	Aboveground Biomass + Soil	Only Above- ground Biomass
Reference level	10	100	50	1500	1000
Assessment period	5	100	50	750	500
Reduction of emissions (reference level - assessment period, t C x 10 ³)				750 (a)	500 (b)

6498

6499 **4.4.2 Addressing uncertain estimates**

6500 Assuming that during the “estimation phase” the Party carries out all the practical efforts
 6501 to produce accurate and precise REDD estimates (i.e., to reduce uncertainties), as well
 6502 as to quantify the uncertainties according to the IPCC guidance, here we suggest a
 6503 simple approach to deal with at least part of the remaining uncertainties.

6504 Similarly to the adjustment procedure under Art. 5.2 of the Kyoto Protocol (see before),
 6505 we propose to use the confidence interval in a conservative way, i.e. to decrease the
 6506 probability of producing an error in the unwanted direction. Specifically, here we briefly
 6507 present two possible approaches to implement this concept:

6508 Approach A): the conservative estimate of REDD is derived from the uncertainties of
 6509 both the reference and the assessment periods. Following the idea of the Reliable
 6510 Minimum Estimate (IPCC GPG LULUCF 2003), the aim is to decrease both the risk of
 6511 overestimating the emissions in reference period and the risk of underestimating the
 6512 emissions in the assessment period. Therefore, this approach calculates the difference
 6513 between the lower bound of the confidence interval (i.e., downward correction) of
 6514 emissions in the reference period and the higher bound of the confidence interval (i.e.,
 6515 upward correction) of emissions in the assessment period (see Fig. 4.4.2.A).

6516 Approach B): the conservative estimate of REDD is derived from the uncertainty of the
 6517 difference of emissions between the reference and the assessment period (uncertainty of
 6518 the trend, IPCC 2006 GL, as illustrated in Fig. 4.4.2.B). From a conceptual point of view,
 6519 this approach appears more appropriate than approach A for the REDD context, since
 6520 the emission reduction (and the associated trend uncertainty) is more important than the
 6521 absolute level of uncertainty of emissions in the reference and assessment period. A
 6522 peculiarity of the uncertainty in the trend is that it is extremely dependent on whether
 6523 uncertainties of inputs data (Activity Data, AD, and Emission Factor, EF) are correlated
 6524 or not between the reference and the assessment period. In particular, if the uncertainty
 6525 is correlated between periods it does not affect the % uncertainty of the trend (see Ch.
 6526 2.6.3.3 for further discussion on correlation of uncertainties). In uncertainty analyses of
 6527 GHG inventories, no correlation is typically assumed for activity data in different years,
 6528 and a perfect positive correlation between emission factors is assumed in different years.
 6529 This is the basic assumption given by the IPCC (IPCC 2006 GL), which we consider likely
 6530 also in the REDD context.

6531

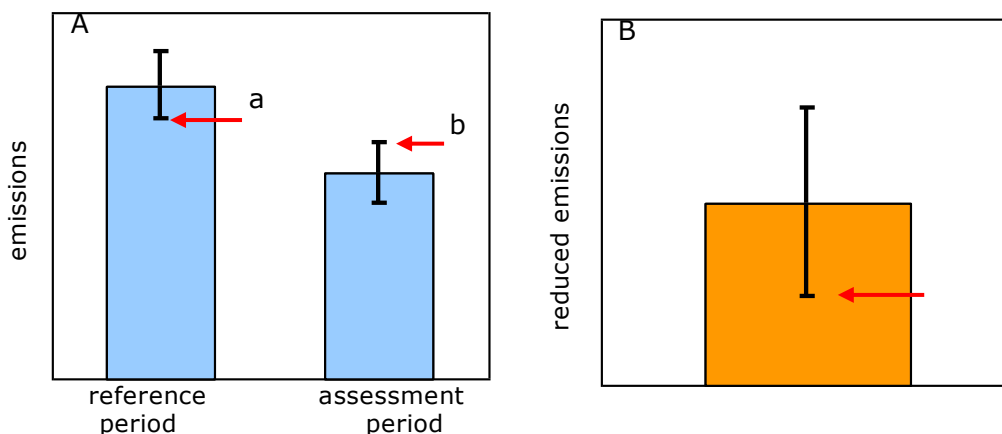
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6536



6537 **Figure 4.4.2.** With approach A (left), the conservative estimate of REDD is calculated
 6538 based on the uncertainties of both the reference and the assessment period (a - b). With
 6539 approach B (right), the conservative estimate of REDD is derived from the uncertainty of
 6540 the difference of emissions between the reference and the assessment period
 6541 (uncertainty of the trend).

6542 Further discussions on possible ways of applying conservativeness to uncertain estimates
 6543 may be found in Grassi et al. (2008).

6544 Our proposal of correcting conservatively the REDD estimates may be potentially applied
 6545 to those estimates which do not fulfill the IPCC's good practice principles (e.g. if a key
 6546 category is estimated with tier 1: country-specific estimates of AD combined with IPCC-
 6547 default EF). In this case, the corrections could be based on the uncertainties of AD
 6548 quantified by the country appropriately combined to the default uncertainties of EF used
 6549 under Art. 5.2 for the various categories and C pools.

6550

6551 Our proposal of correcting conservatively the REDD estimates may be based on the
6552 uncertainties quantified by the country when estimated in a robust way (that will be
6553 subject to subsequent review). In absence of such estimates from the country, the
6554 confidence intervals may be derived from tabulated category-specific uncertainties,
6555 possibly produced by the IPCC or other independent bodies (as in the case of Art. 5.2 of
6556 the Kyoto Protocol).

6557 In any case, during the review phase, the reported AD and EF will be analyzed. If the
6558 review concludes that the methodology used is not consistent with recommended
6559 guidelines by IPCC or with the UNFCCC's principles, and may produce overestimated
6560 REDD data, the problem could be addressed by applying a default factor multiplied by a
6561 conservative factor (as already described for Art. 5.2 under the Kyoto Protocol).

6562

6563 **4.4.3 Conclusion: conservativeness is a win-win option**

6564 The IPCC defines inventories consistent with good practice as those which contain
6565 neither over- nor underestimates so far as can be judged, and in which uncertainties are
6566 reduced as far as practicable. Consequently, also REDD estimates should be complete,
6567 accurate and precise. However, once the country has carried out all the practical efforts
6568 in this direction, if still some aspects do not fulfill the IPCC's good practice (e.g. if a key
6569 category is not estimated with the proper tier, or if the emissions from a significant C
6570 pool is not estimated), the remaining problems could be potentially addressed with the
6571 conservativeness concept, to ensure that reductions in emissions or increases in
6572 removals are not over-estimated. To this aim, in Sections 4.4.1 and 4.4.2 we proposed
6573 few examples of how the conservativeness approach can be applied to an incomplete
6574 estimate (e.g., an omission of a pool) and to an uncertain estimate. In the REDD
6575 context, the conservativeness approach has the following advantages:

6576 - It may increase the robustness, the environmental integrity and the credibility of
6577 any REDD mechanism, by decreasing the risk that economic incentives are given to
6578 undemonstrated reductions of emission. This should help convincing policymakers,
6579 investors and NGOs in industrialized countries that robust and credible REDD estimates
6580 are possible.

6581 - It rewards the quality of the estimates. Indeed, more accurate/precise estimates
6582 of deforestation, or a more complete coverage of C pool (e.g., including soil), will likely
6583 translate in higher REDD estimates, thus allowing to claim for more incentives. Thus, if a
6584 REDD mechanism starts with conservativeness, precision and accuracy will likely follow.

6585 - It allows flexible monitoring requirements: since the quality of the estimates is
6586 rewarded, it could also be envisaged as a system in which - provided that
6587 conservativeness is satisfied, - Parties are allowed to choose themselves what pool to
6588 estimate and at which level of accuracy/precision (i.e. Tier), depending on their own
6589 cost-benefit analysis and national circumstances.

6590 - It stimulates a broader participation, i.e. allows developing countries to join the
6591 REDD mechanism even if they cannot provide accurate/precise estimates for all carbon
6592 pools or key categories, and thus decreases the risk of emission displacement from one
6593 country to another.

6594 - It increases the comparability of estimates across countries - a fundamental
6595 UNFCCC reporting principle - and also the fairness of the distribution of eventual positive
6596 incentives.

6597

6598 **4.5 KEY REFERENCES FOR CHAPTER 4**

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This sourcebook is the outcome of an ad-hoc REDD working group of "Global Observation of Forest and Land Cover Dynamics" (GOFC-GOLD), a technical panel of the Global Terrestrial Observing System. GOFC-GOLD provides an independent expert platform for international cooperation to formulate scientific consensus and provide technical input to the discussions. This first draft version provides a consensus perspective from the global community of earth observation and carbon experts on methodological issues relating to quantifying the green house gas impacts of implementing activities to reduce emissions from deforestation and degradation in developing countries (REDD). Based on the current status of negotiations and UNFCCC approved methodologies, this sourcebook aims to provide additional explanation, clarification, and methodologies to support REDD early actions and readiness mechanisms for building national REDD monitoring systems. Respective communities are invited to provide comments and feedback to evolve a refined technical-guidelines document in the future.

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