Estimating the opportunity costs of REDD+

A training manual

Version 1.3

Chapter 4. Land use & land use change

Objectives

Show how to:

1. Develop a national land use framework and legend,
2. Create land use maps,
3. Validate land use maps,
4. Estimate land use change,
5. Explain land use change.

Contents

Introduction

1. This chapter describes how to classify land uses, estimate land use change, and explain land use change, thereby providing vital information for opportunity cost analysis. The approach is based on identifying different land use systems common within a country. These land use systems range from forests to agriculture, pasture, and urban areas.

2. A series of steps are presented to generate land use maps and assess land use change. In addition, the chapter explains how to acquire, organize, and classify remote sensing data and how to validate the accuracy of the derived maps. The approach described in this module is largely based on the GOFC-GOLD REDD Sourcebook, which should be consulted for in-depth guidelines on land use and land cover mapping (GOFC-GOLD, 2009). For detailed technical information related to developing land use maps, the chapter directs practitioners to additional sources. Deforestation monitoring and MRV activities should be consistent with other studies employing similar methods, independent of the scale and detection technologies used. For predicting land use change, important to develop scenarios, different modeling approaches are briefly presented.

3. In sum, this chapter provides guidance to produce the following outputs for opportunity cost analysis:

    1. Land use framework and accompanying legend,
    2. Land use maps of different dates,
    3. An error analysis to assess the accuracy of the maps,
    4. Land use change matrices,
    5. Deforestation drivers and land use transitions
    6. Predicting land use change

4. Land use analysis has its own vocabulary. For definitions, please refer to the Glossary in **Appendix A**.

Spatial analysis and remote sensing words

Land cover
Land use
Land use system
Classification system
Land use legend
Land use trajectory
Attribute table

Resolution
  Spectral
  Spatial
Ground truth
Minimum mapping unit
Mixed mapping unit
Vector GIS
Raster GIS

Identifying land uses

5. Although land cover and land use are related, they are not the same. Within a country, matching land covers (e.g. vegetation types) identified from satellite images with actual land uses on-the-ground is one of the greatest challenges of land use mapping (Cihlar and Jansen, 2001).

6. Remote sensing experts and specialists with field knowledge of specific geographic areas (e.g. land managers, scientists, and government staff) are needed to identify and classify land uses. The opportunity cost analysis team should ensure that categories are compatible with monitored land cover classes and are consistent with carbon content and economic activities.

Land cover ≠ Land use

7. To enable correct and consistent use of land use information (e.g., carbon, profits) for opportunity cost analysis at a national level, a **hierarchal land use framework can be** employed (Figure 4.1).

A national land use framework for REDD+

8. An initial step in developing a national land use framework is to identify the current state of land use mapping in the country. Since many countries already have a national land use framework, a literature search and acquisition of existing maps is essential. If him will he existing frameworks are unsuitable for the opportunity cost project, the project team will need to improve these frameworks in line with the requirements of the project. The discussion below serves as a guide to decide whether to use and adapt an existing framework or develop a new one.

9. The most important consideration for developing a workable national land use classification framework for an opportunity cost analysis is compatibility of resolutions between land use, economic and carbon information. A meaningful classification scheme must account for variation of carbon and profits across the landscape and country. Many factors cause variation, including:

1. Agro-ecology climate and/or topographic zones,
2. Soils, special consideration is needed for:
   a) wetland, peat, mangrove, volcanic soils with potentially high C losses,
   b) 'poor soils' of low profitability yet potential gain in C stocks,
3. Policy, institutional and management boundaries (agriculture and forest zones, tenure systems, etc.),
4. Accessibility characteristics of transport infrastructure (e.g. paved road, dirt road, river, etc.),
5. Preceding uses of land, which can affect soil fertility and carbon content.

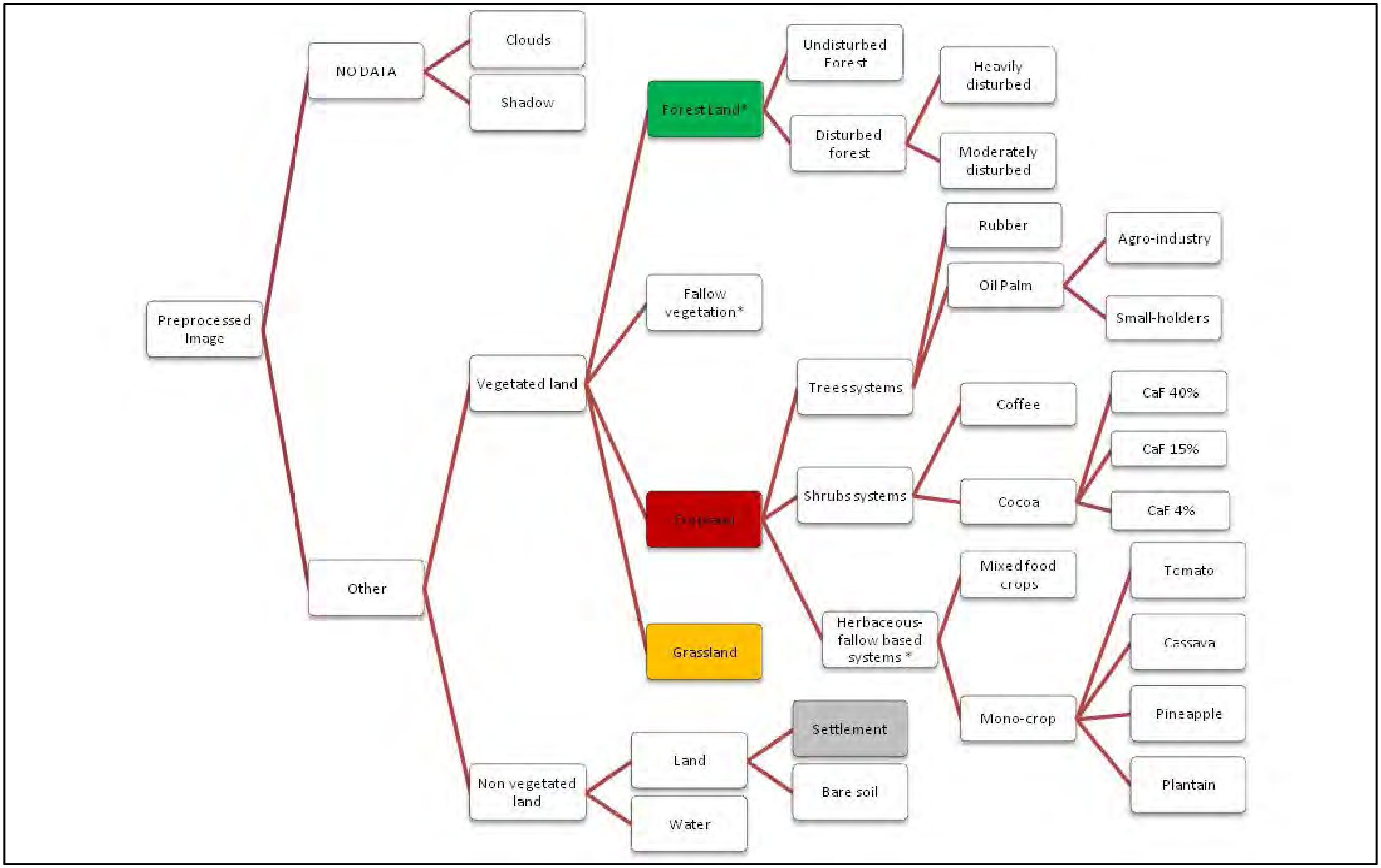

Figure 4.1. A hierarchical land use framework in Cameroon humid forest zone.[39]

Source: Robiglio, 2010.

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[39] Caf: Cocoa Agroforest with different levels of shade trees coverage. Forest classes are defined on the basis of the level of disturbances/degradation. Classes may be associated to different types of management (Community Forest, Council Forest, Protected Areas) that provide for different intensities of logging.

10. How many land use classes? The selected number of class categories depends on: availability of geographic data and analysis, ability to detect differences in land cover on remote sensed imagery (image resolution), availability of carbon and profitability information of land uses, and the desired rigor of the opportunity cost analysis. Such a variety of factors points to a need for a multidisciplinary team with a clear understanding of opportunity cost analyses in the context of REDD+ programs.

11. Splitting land uses into sub-classes is needed if a class does not accurately represent a land use in terms of carbon stock or net returns. Soil properties or uses may differ within the same land cover. Different levels of net returns within a class may arise on the basis of accessibility and location. Profitability for the same crop may vary, depending on whether it was produced near to or far from the market.

12. On the other hand, aggregating (lumping) classes together may be needed. One reason is technical. The minimum mapping unit (MMU) of imagery may not be small enough to differentiate classes; thus a mixed mapping unit is required. Simplifying the land use framework is another reason. A lower number of classes requires less data management and analysis. In addition, a false sense of precision may arise by creating numerous sub-classes from inadequate resolution of images, carbon or profit information.

13. Note that the level of detail in a land use framework needs not be the same throughout the country. A greater level of detail may be used in areas that are of particular interest, or to take advantage of better available data in some areas. Moreover, the level of detail need not be static. As additional information becomes available, land use categories might be split into sub-categories. Alternatively, previously separate categories might be joined together if the differences are found to be less than anticipated. In this as in many aspects of estimating the opportunity costs of REDD+, it is useful to think of the work as an iterative process rather than a one-time task. In sum, decisions about splitting or aggregating classes will be guided by the level of spatial detail in the mapping process and the availability of ancillary data about biophysical and socio-economic/infrastructural or management data.

Table 4.1 shows a land cover and land use classification with three levels of hierarchy. This mixed classification system was part of an international effort to map deforestation in the tropics (Puig, et al., 2000; Achard, et al., 2002). The first level contains broad classes of land cover such as forest, agriculture and mixed covers. The second level includes land cover types of greater detail. The third level is even more specific, including some land types that are specific to certain sub-national regions. A fourth level (not depicted) only refers to forest, using percent canopy cover as distinguishing criteria. In this example, - differences in canopy cover (land cover) could be used to detect levels of selective logging (land use). Once the framework has been defined, the project team can focus on the logistics of remote-sensing analysis and the making of land cover and land use maps. During later stages of the analysis process, the analysts may need to revise the legend further.

Table 4.1. A legend from a hierarchical land cover classification system

Level 1		Level 2		Level 3			
1	**Forest**	*> 10% canopy Cover and > 40 % forest cover **					
	Forest	1	Evergreen & Semi-evergreen Forest	0	Unknown	4	Heath forest / Caatingas
				1	Evergreen – lowland forest	5	Coniferous 6. Bamboo forest
				2	Evergreen – mountain forest	9	Other
				3	Semi-evergreen forest		
		2	Deciduous Forest	0	Unknown	3	(Dry-) Mixed deciduous (Asia)
				1	'Dense dry' forest (Africa)	4	Dry Dipterocarp' (Asia)
				2	Miombo' (Africa)	9	Other
		3	Inundated Forest	0	Unknown	3	Swamp forest with palms Aguaj.
				1	Periodically inundated –Varzea	4	Peat swamp forest
				2	Swamp forest (perm. Inundated)	9	Other
		4	Gallery-forest	0			
		5	Plantation	0	Unknown	3	Eucalyptus
				1	Teak	9	Other
				2	Pine		
		6	Forest Regrowth	0			
		7	Mangrove	0			
		9	Other	0			
2	**Mosaic**	*>10% - 40 % forest cover (and > 10% canopy cover)*					
	Mosaic	1	Shifting Cultivation	0	Undefined		
				1	≤ 1/3 cropping		
				2	> 1/3 cropping		
		2	Cropland & Forest				
		3	Other Vegetation & Forest				
		9	Other				
3	**Non-Forest Natural Vegetation**	*≤ 10% forest cover or < 10% canopy cover*					
	Non-Forest Natural Vegetation	1	Wood & shrubland	0	Unknown	5	Swamp savanna
				1	Woodland savanna – Cerrado]	6	Humid (evergreen) type (Asia)
				2	Tree savanna	7	Dry (savanna) type (Asia)
				3	Shrub savanna	9	Other
				4	Bamboo (pure stands)		
		2	Grassland	0	Unknown		
				1	Dry grassland		
				2	Swamp grassland –varzea		
				9	Other		
		3	Regrowth of vegetation				
		9	Other				
4	**Agriculture**	*≤ 10% forest cover or ≤ 10% canopy cover*					
	Agri-culture	1	Arable	0 Unknown, 1 Irrigated, 2 Rain-fed			
		2	Plantations	0	Unknown	3	Coffee, Cacao, Coca
				1	Rubber	9	Other
				2	Oil Palm		
		3	Ranching				
		4	Small holdings				
		9	Other				
5	**Non-vegetated**						
	Non-vege-tated	1	Urban				
		2	Roads				
		3	Infrastructure	1 Mining, 2 Hydro-electric, 9 other			
		4	Bare soil				
		9	Other				
6	**Water**						
	Water	1	River				
		2	Lake	1 Natural, 2 Artificial			
7	**Sea**						
8	**Not visible**						
	Not visible	1	Clouds				
		2	Shadow				
9	**No data**						

Source: Puig et al., 2000

14. A land use legend is the map key that expresses each class as a distinct color or pattern on the map. In this manual, classes and sub-classes in a land cover legend are matched with land uses. Thus, at the end of the classification process, the hierarchical land use framework spans from general global land cover classes to local land use classes. The land use legend is the basis for identifying land covers and mapping land uses.

15. The land use legend must match a land cover legend that follows best practices for mapping, and meets additional criteria for compatibility with a REDD initiative (Cihlar and Jansen, 2001; GOFC-GOLD, 2005; Herold et al., 2006; IPCC, 2006; Herold and Johns, 2007). One of the best resources for developing the legend is the Land Cover Classification System[40] (LCCS; Di Gregorio, 2005). The LCCS includes a thorough description of classification concepts and guidelines for matching land cover types to global standards.

Steps to identify land uses

- *Consult the literature*. Cihlar and Jansen (2001) provide an overview on how to match land covers with land uses. Case studies from Lebanon and Kenya are practical examples (Jansen and Di Gregorio, 2003; Jansen and Di Gregorio, 2004)
- *Check map availability:* Reviewing previous land use change analysis is an important early task. Available land cover and land use maps may only need small modifications for use in an opportunity cost analysis. For example, existing land cover and land use maps may be suitable for developing a land use legend for lower rigor opportunity cost analyses (Tiers 1, 2).
- *Develop decision rules to convert land cover classes to land uses.* Rules will most often be based on local expert knowledge. For example, small patches of forest and cleared areas (land cover) shown in remote sensing data indicate shifting cultivation (land use). These decision rules should be put into a table for reference.
- *Collect land use information during fieldwork activities.* One assumption of the analysis is that all land cover classes can be matched to all land uses. The fieldwork should confirm and validate the rules matching land cover with land use.
- *Confirm land cover and land use data.* Monitoring, reporting and verification (MRV) activities are an opportunity to confirm the match between land cover and land use.
- *Consider image resolution when developing land use legend:* Different land uses may look the same on a satellite image (e.g. intensive or extensive agriculture or the degree of forest degradation). Mixed mapping units are used if the elements composing a mapping unit are too small to be delineated independently.

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[40] The LCCS manual and software can be acquired from the Global Land Cover Network website (http://www.glcn.org/).

Box 4.1. Data management and analysis

Analysis of land use change requires careful management of data. The data management principles of an opportunity cost analysis are similar as those for REDD activities, such as monitoring, reporting and verification (MRV) of carbon stock data. Developing a system for data management and analysis described above requires a substantial investment. Costs will depend on the size of the country, existing expertise and resources and other factors. For example, to build a national-level MRV system – something outside the normal scope of an opportunity cost analysis – Herold and Johns (2007) estimated a cost between several hundred thousand and US$2 million. Given these high costs, a national team conducting opportunity cost analysis has incentives to collaborate with and build on existing work and expertise. If your country has an MRV system, most or all of the information needed for the analysis may be available.

Countries that lack MRV systems will need to identify experts who have the resources to be able carry out the land use change analysis and develop a robust information system for analyzing opportunity costs. If you were to build an information system for the land use change assessment of an opportunity cost analysis from scratch, five elements are needed: human resources, data and documentation, analytical methods, hardware and software.

1. **Human resources**: Expertise will be needed in remote sensing and geographic information systems (GIS) science and technology. Remote sensing experts should have prior experience producing land use and land cover maps. Experts should know how to pre-process data for subsequent classification and analysis, including knowledge of coordinate systems and data registration. Specialists should ideally have experience with visual interpretation of imagery, digital image processing, supervised and unsupervised classification and image segmentation. Experts should know how to conduct field work with global positioning systems and digital photography. Personnel typically have a Masters degree or equivalent experience in fields that use remote sensing and GIS methods.

2. **Data and documentation**: An inventory of data needed should be made to determine the feasibility of acquiring imagery, and whether additional expenditures will be needed. If a national MRV activity is not yet established or no remote sensing data or classified land cover information is available, the costs (time and money) of acquiring data and their analysis must be considered. Documenting data, methods and results of any opportunity cost analysis is a high priority. Context and description of data (or metadata) are needed, especially since the analysis requires the participation and contribution of many types of scientific expertise and participants may change over time. Documentation enables analysis to be repeatable and meet peer-review quality standards. The IPCC (2006) or other international standards can serve as guidelines. For remote sensing and spatial data, a national effort should produce metadata that meets the standards of the International Standards Organization (ISO) or the U.S. Federal Geographic Data Committee (FGDC). An opportunity cost analysis, or REDD effort should align itself with any national efforts to develop national spatial data infrastructure (NSDI).

More information on geospatial metadata can be found through the Global Spatial Data Infrastructure (GSDI).

3. **Analytical methods**: The complexity and targeted level of analysis will determine the analytical methods employed. Any country can draw on an extensive GIS and remote sensing literature.

4. **Hardware**: Required capacity of the computer hardware will also depend on the rigor of the analysis. Personal computers with large hard drives and ample memory (i.e. RAM) are typically sufficient.

5. **Software** options for land use analysis may be freely-available open source or proprietary, including: Google Earth, GRASS (http://grass.itc.it/), SPRING (Camara, et al. 1996), ILWIS (http://www.ilwis.org/), low-cost IDRISI (Eastman, 2009), ArcGIS from Environmental Systems Research Institute (ESRI) and other software packages. The capacity of the software to identify appropriate characteristics must be considered. For example, do the image interpretation algorithms work well in tropical contexts?

Creating land use maps

16. This section is a general overview of available remote sensing (RS) techniques and associated challenges of developing land use maps for opportunity cost analysis. An extensive handling of the tools for estimating, accounting and reporting on land cover and carbon stocks is found in the IPCC Good Practice Guidance and the GOFC-GOLD REDD Sourcebook (IPCC, 2006; GOFC-GOLD, 2009).

Remote sensing data

17. Remotely sensed information comes from different sources, each with unique resolution, frequency (i.e., orbit cycle) and cost (Table 4.2). Two websites are useful for acquiring remote sensing data: the United States Geological Survey's GLOVIS site (http://glovis.usgs.gov/) and the Global Land Cover Facility at the University of Maryland (http://glcf.umiacs.umd.edu/index.shtml). Remote sensing specialists are advised to consult the GOFC-GOLD Handbook (2009) for a complete discussion of the considerations related to selecting remote sensing imagery.

Table 4.2. Characteristics of satellite images

Satellite	Sensor	Resolution (Spatial)	Orbit cycle	Image cost
TERRA	MODIS	250 m	2 days	Low
		500 m		
		1000m		
LANDSAT 7	ETM+	15 m (185 km)	16 days	Medium
		30 m (185 km)		
DMC II		32 m (80x80 km)	1 day	Medium
SPOT 1-3	XS	20 m (60x60 km)	26 days	Medium
	PAN	10 m (60x60 km)		
SPOT 4	XS	20 m (60x60 km)	26 days	Medium
	PAN	10 m (60x60 km)		
	VGT	1 (2000 km)		
SPOT 5	HRS	10 m (60x60 km)	26 days	Medium
	HRG	5 m (60x60 km)		
TERRA	ASTER	15 m		Medium
		30 m		
IRS-C	Pan	5.8 m (70 km)	24 days	Medium
	LISS-III	23 m (142 km)		
IKONOS	PAN	1 m (min10 x 10 km)	3 days	High
	MS	4 m (min10 x 10 km)		
QUICKBIRD		2.5 m (22x22 km)	3 days	High
		61 cm (22x22 km)		
ALOS	PRISM	2.5 m (70 km)	46 days	High
	AVNIR2	10 m (70 km)		
	PALSAR	10 m (70km)		

Source: Adapted from GOFC-GOLD, 2010.

18. One satellite data option is high resolution imagery such as IKONOS and Quickbird. Such remote sensing data, however, becomes more expensive with smaller minimum mapping units (MMU) and require substantial computing power to be able to manage large quantities of small pixels. Moreover, geographic coverage of high resolution imagery is limited, especially in many areas of the tropics.

19. In contrast, low resolution imagery (large MMUs) are widely available at low cost. For example, MODIS images have 250m spatial resolution and can be freely downloaded from the Internet. The poor resolution, however, makes it difficult to distinguish land classes. This

problem is compounded in the humid tropics where landscapes often contain small agricultural plots (Figure 4.2).

Figure 4.2. A spatially heterogeneous farm landscape in Cameroon.
Source: Robiglio, 2009.

20. Medium resolution imagery such as Landsat and Aster represent an attractive compromise of resolution and cost (Figure 4.3). An important advantage of Landsat is the availability of older images to establish a baseline for determining medium-term deforestation rates. However, Landsat 7 has a sensor error that seriously limits image use since 2003. Therefore, the analyst should consider alternative sensors to overcome gaps in recent images.

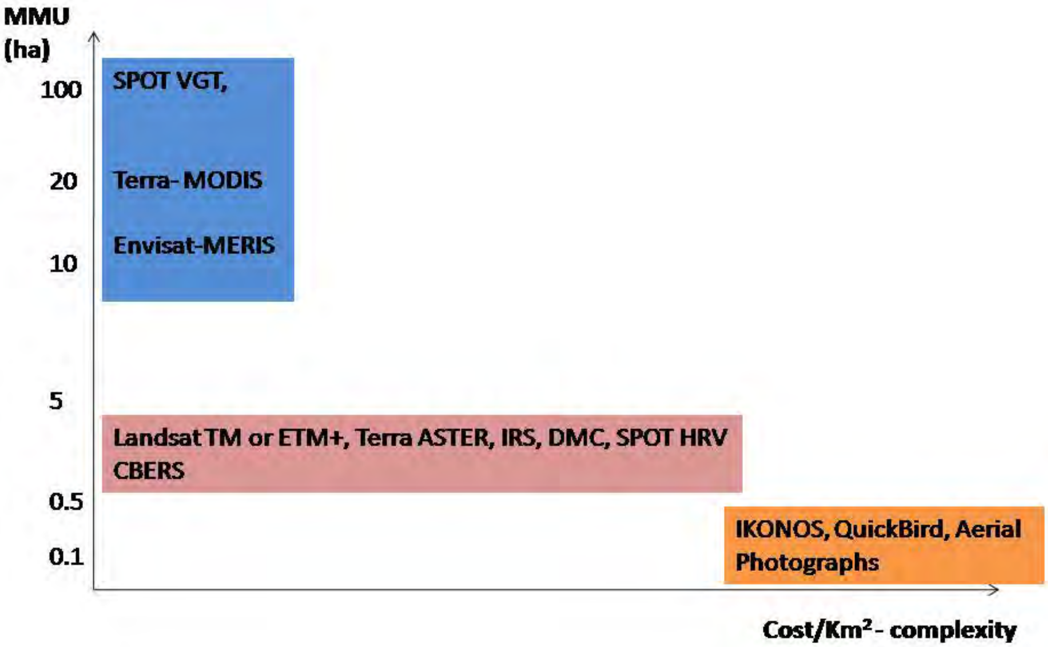

Figure 4.3 Remote sensing data: cost and complexity versus resolution (MMU)
Source: Authors

21. The remote sensing data options described above are standard alternatives. Nevertheless, land use and carbon stock assessments may be able to take advantage of new methods and approaches to monitoring and measuring deforestation, forest degradation and land use change (see discussion on LIDAR in Box 4.4 below). As they become available and accepted, analysts can consider these new approaches.

Box 4.2. Estimating carbon stocks from biomass maps versus land use maps

Remote sensed imagery can be useful to estimate carbon in biomass and understand the geographic distribution of carbon across a landscape (Baccini, 2004; Foody, et al. 2003, Goetz et al. 2009). For example, Saatchi et al. (2007) estimated total carbon of 86 Pg C from their remote sensing assessment of aboveground live biomass in the Amazon. Biomass levels varied with the length of the dry season and across the landscape.

Biomass assessments have less relevance for calculating the opportunity cost of avoided deforestation. Opportunity cost calculations require information on land uses with associated C content (see Chapter 5) and profitability measures. Only from land use, can the net present values of economic activities be estimated.

Image analysis

22. Remote-sensing requires preprocessing of the satellite imagery. Such work often includes image geo-referencing and radiometric correction to account for atmospheric distortions. Nevertheless, many remote-sensing providers deliver satellite imagery that has

already been pre-processed. Standard methods to conduct the preprocessing are available in the remote sensing literature (for example, see Jensen, 1995; Lillesand and Kiefer, 2000).

23. In general, three methods are available to interpret remote-sensing imagery: (1) visual interpretation, (2) pixel-based digital image processing, and (3) image segmentation. To date, there is no consensus in the REDD literature on the best method. Selection of the interpretation method may depend on national human resource capacities, on the relative costs of the different methods, and on the characteristics and size of the area.

1. *Visual interpretation.* Analysts draw polygons around visible differences in the satellite images on the computer screen (Puig et al., 2002). The polygons are associated with a class from the land cover legend. An advantage of this method is that recent imagery can be updated using the base map from an initial date. A disadvantage is that the method is more subjective than other methods, depending on analyst judgment. In addition, for large countries, visual interpretation may be impractical and time-consuming.

2. *Pixel-level digital image processing.* Computer algorithms are used to conduct unsupervised and supervised classifications. Most digital image processing in the past has been conducted at the pixel level (Jensen, 1995). Each pixel is considered a land unit and is clustered into groups of similar pixels. The clustering may be based only on the digital number of the pixel, a method referred to as unsupervised classification. With supervised classification, however, an analyst assigns pixels representing a land cover to a class in the legend. This second method depends on the analyst knowledge of the study area. Digital image processing is more objective compared to visual interpretation, as it depends on computer algorithms to assign pixels to land classes.

3. *Image segmentation.* Recent remote-sensing software includes image segmentation methods to classify land cover and land use (Camara, 1996; Eastman, 2009). An algorithm clusters groups of pixels together based on their spectral responses and a set of rules established by the analyst. An advantage of this approach is relatively low cost over large areas. Nevertheless, careful linking of land cover with land use ground truth information is needed to avoid large scale errors.

24. After an image interpretation method is selected, an analysis can be conducted and digital maps produced. The next step will be validation of the results. Analysts will need to review and improve image interpretation processes and results, depending on the outcome of the verification and validation analysis. In general for tropical land uses, a high level of expert judgment and ground knowledge are needed.

Box 4.3. The challenge of identifying forest degradation

Forest degradation is a reduction of tree density, measured by canopy cover or stocking, within the forest (Schoene, et al., 2007). Forests are degraded by human or natural causes. The magnitude/intensity of degradation monitored depends on the definition of forest. For example, if a country identifies forest with a minimum surface of 0.5 ha then a loss of forest smaller than 0.5 would be reported as degradation. Losses of areas higher than 0.5 ha would be considered deforestation. A similar logic can be applied to other forest definition thresholds for canopy cover and height. For a discussion of the importance of definitions, see Sasaki and Putz (2009), van Noordwijk and Minang (2009) and Guariguata et al. (2009).

Degradation can be difficult to identify on satellite images. Forest inventory plots can produce accurate biomass and carbon estimates yet results are site specific (see Harris, et al. 2010) In the land use legend presented earlier in this chapter, forest degradation is accounted for by identifying the different levels of canopy cover. Associated spatial data may be used to identify areas where degradation may be occurring (e.g. in logging concessions). Forest density and tree coverage can be estimated using expert judgment, LIDAR (Light Detection and Ranging) or multispectral 3-dimensional aerial digital imaging.

Identification of forest degradation is a hot topic in remote-sensing research. Asner (2009) has developed a method to combine traditional satellite mapping approaches with an active airborne, laser technology approach called. LIDAR produces information on the height of trees, crown diameter and the structure of the forest, making it especially useful for determining whether a forest has been selectively logged over. More recently, LIDAR combined with MODIS imagery was used to map tree canopy height over the entire world (Lefsky, 2010).

M3DADI uses (1) GPS-based techniques to identify tree crown mosaics, and (2) off-the-shelf camera equipment mounted on Cessna aircraft to generate accurate raster-based photomaps. From the aerial videography, a 3D reconstruction is developed that identifies terrain features and vegetation types and measures the height and mass of individual trees. The measurements are then calibrated with the carbon inventory data and regression equations to estimate carbon remotely (Stanley, et al. 2006).

The time costs for the field sampling approach were about 2.5 to 3.5 times longer than for the M3DADI approach to achieve the same precision level. Although M3DADI has high fixed costs, the costs for additional plots are low (Brown and Pearson, 2006). Another advantage of remote-sensing approaches is that the data provide a permanent record of what was found in a given location at any given time. The images can be re-visited and verified, or new assessment techniques applied to historical data to improve historical estimates (Stanley, et al. 2006).These new method and others promise to improve our capacity to cost-effectively identify forest degradation.

Checking accuracy

25. Are the land use estimates accurate? Validation of land cover and land use classification is a standard practice that opportunity cost analysis must include. Accuracy assessment and

validation of land uses are important to assure the credibility of land use change estimates. This section discusses (1) sources of error and uncertainty, and (2) the validation process.

Sources of error and uncertainty

26. An analysis should identify the sources of error and their magnitude. With this information, the analysis team can revise the work in an effort to reduce these problems.

27. Using multiple images – across the study area or for different dates – requires a separate classification process for each individual scene. These differences in the images and in the processing may lead to inconsistencies in quality of the classification for the study area. For example, a challenge could arise related to the timing of imagery. Interpretations may reflect errors due to varying vegetation vigor if different nearby image scenes were captured at different times of the year. If one scene was captured in the dry season and another in the wet season, the classification may reflect seasonal differences in vegetation, and not the longer-term land cover and land use.

28. Another typical challenge to land use mapping in the tropics is cloud cover. The analyst will need to acquire additional images for areas covered by clouds. Otherwise, areas with cloud cover must be left out of the analysis. Future technological development for the use of Radar and LIDAR images could help overcome cloud problems.

29. Cloud cover is a persistent problem, in particular in the coastal countries of Central Africa. The improved accessibility to SPOT images (Mercier, 2010) and the establishment of an Earth Observation Receiving Station for the Central African region in Gabon (Fotsing, et al. 2010) are expected to facilitate RS mapping and consistent monitoring of forest cover change in the area.

30. Acquiring imagery with appropriate spatial resolution is also a potential challenge. Difficulties arise when interpreting smallholder agriculture and degraded forests. A key task is to ensure that the resolution of the remote sensing imagery can capture land cover and related land uses that are relevant for the analysis. Expert use of the definition and composition of *mixed mapping units* for land use mosaics can help overcome problems of inappropriate spatial resolution.

Validation process

31. Validation methods can be found in textbooks and the remote sensing literature and should be consulted in depth (Jensen, 1995; Lillesand and Keifer, 2000; Congalton, 1991; Foody, 2001; Congalton and Green, 2009). This section briefly describes the general process to conduct a validation exercise for land cover and land use maps.

32. Validation requires information on the “true condition” of land use throughout the study area. Information can come from two sources: 1) *ground truthing*, or 2) reference data.

1. *Ground-truthing* is a remote sensing term for field verification. To acquire such information, a field survey is conducted to collect ground characteristics at sample points using a comprehensive sampling scheme. One way to develop sample points is by using random point generators within a GIS to assign locations to be verified. The points should cover as much as possible the variation in the RS imagery. Nevertheless, no well-established rule exists on how many data points are needed for the validation. One rule of thumb, however, is that 30 to 50 points are needed for each land cover / land use class.

   The key technologies and tools needed for the field validation are spreadsheets, databases, global positioning systems (GPS), and digital cameras. An available field ve*rification protocol* document includes a sample survey form for recording information.[41] The field team records the data in a standardized form. With *ground truthing,* the ability of survey team to access all parts of a study area may be limited. Many areas lack roads or present difficult terrain, making a representative sample of land uses and covers difficult to acquire. Therefore, sampling schemes need to be somewhat opportunistic, taking most points in places where access is low-cost and practical. (See Box 4.5 for other cost-savings approaches.)

2. Reference data are imagery or maps with a high degree of validity. The most common reference data are very high resolution imagery (VHRI), which may have spatial resolutions of 1 m, a level of detail that enables validation against land cover and land use classification. Common sources of VHRI include Quickbird and IKONOS. For some areas, virtual globes such as Google Earth and Microsoft Virtual Earth often include VHRI, displayed in their optical bands. Limitations to their use include an inability of the optical range to discern differences in some land uses, and a suitability of image date for comparisons.

Box 4.4. Optimizing activities in the field

Fieldwork in the study area can accomplish multiple objectives at the same time. For example, while researchers are taking plot level measurements of biomass, digital photographs and global positioning system (GPS) points can be collected with notes on the land conditions.

Before image interpretation, field work is needed to identify homogenous land units for classification. During field work, the analysis team can collect on-the-ground information that can be used for training and validation. To avoid any confusion, two different data sets have to be created – one with training points and the other with points for validation.

Ground-truth information should be managed in a data management system. For example, the figure below shows a Google Earth interface to photographs, GPS points and field notes

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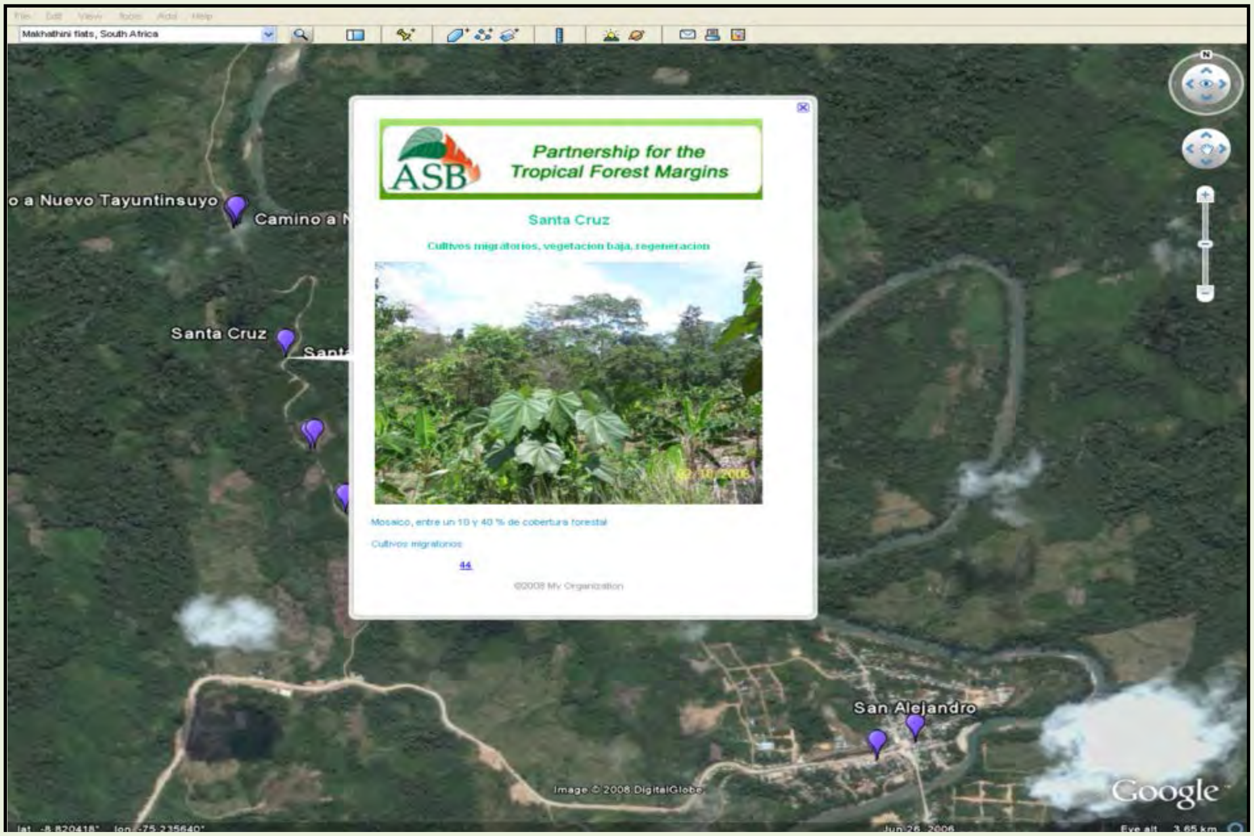
[41] The CIFOR-ICRAF-Biodiversity Platform has produced a document titled "Ground-truthing Protocol," available from http://gisweb.ciat.cgiar.org/GoogleDocs/FPP_Mapper/groundtruth_protocol.pdf.

stored in an online spreadsheet. The study area was visited in a *ground truthing* campaign in the central Peruvian Amazon. To match photographs with locations, timestamps of the digital photos were matched with timestamps of the GPS point.



Example photograph of a ground-truth point within a landscape

33. After the "true" land cover or land use has been determined for sample points, comparison with the classified map can begin. The recorded validation data is digitized into a map with its accompanying attribute table. Then the validation sample map is overlaid on top of the land use map. This point-in-polygon overlay produces a table where one column shows the land use validation information from the field survey or the VHRI. Another column shows the land use from the classification. These two columns of data are then used to create an error matrix (Table 4.3). This example compares a classified map to VHRI in Google Earth. The value in each cell is the number of validation points for each combination of land use designated according to the classified map and to the VHRI.

Table 4.3. An error matrix

Land Cover Classes	1	2	3	4	5	6	7	8	9	Google	Users
1	40					3				43	93.0
2		31				2				33	93.9
3			29		1	3				33	87.9
4				28		4	1		1	34	82.4
5					24	2				26	92.3
6	1	4	1	4	1	36	3	3	3	56	64.3
7				3			30			41	73.2
8	1						4	26		31	83.9
9			1	2			3		21	27	77.8
Landsat	42	35	31	37	26	50	41	37	25	324	
Producers	95.2	88.6	93.5	75.7	92.3	72.0	73.2	70.3	84.0		

LCC Notes: 1-Forest, 95% canopy; 2-Forest, 80% canopy; 3-Forest, 65% canopy; 4-Forest, 50% canopy; 5-oil palm; 6-shifting cultivation; 7-short rotation fallow; 8-large cattle ranches; 9- without vegetation.

Source: White and Hyman, 2009.

34. The error matrix shows the overall number of correctly-classified points, as well as those that were misclassified. Using the results of the point-in-polygon overlay, the analyst fills the error matrix table. The vertical axis of the table represents the map classification based on Landsat images and the horizontal axis represents the VHRI imagery. The "Users" accuracy (far right column in the table) is the number of correctly assigned pixels divided by the total number of assigned pixels in that class, indicating errors of commission when pixels are committed to an incorrect class. The "Producers" accuracy (last row of the table) is the number of correct pixels for a class divided by the actual number of reference pixels for that class, indicating errors of omission when pixels are omitted from their correct class.

35. For example, the upper left-hand cell shows that 40 points were interpreted (from classified map) and verified (from a VHRI in Google earth) as 95% forest canopy. All 40 points were correctly classified, and therefore appear in diagonal set of numbers (shaded cells). Misclassified points are outside the diagonal set of numbers. For example, row 1 column 6 indicates that three points of the map were classified as 95% forest canopy, but according to VHRI were areas of shifting cultivation.

36. The advantage of the error matrix is that it allows the analysts to assess which land use and land cover change combinations have the highest errors. The results of the error matrix are used to review and improve the map. Analysts may conduct several sequences of map improvement and subsequent error assessment, until an acceptable level of an error is attained.

37. Error analysis and validation can be a difficult task. The above description is intended to give an overview of the process of map validation. Documentation of the validation effort must be complete in order for independent experts to assess the quality of the maps.

Estimating land use change

38. This section describes how to calculate land use change. The procedure contains four basic steps.

1. *Prepare*: Ensure that the maps for each individual date use the same classification system and the images are consistent in terms of area covered, season and sensor (spatial and spectral resolution).
2. *Overlay*: Use GIS or image processing software to overlay land use maps from two different dates. The overlay process creates a new table – called an *attribute table* – where each polygon or pixel in the map contains the recorded land use on both the first and second dates.
3. *Simplify*: The attribute table should be reduced to the set of unique combinations of land use change.[42] Each individual polygon contains the land use code for the dates in the land use change analysis. The different land use change combinations are listed for each polygon. In order to reduce the attribute table to unique combinations of land use change, each distinct land use transition must be identified with its areas summed.[43]
4. *Create the land use change matrix*: Information within the attribute table of land use change is an input to develop a land cover change matrix. The area values are summarized for each combination of land use change.

39. More information on methods and procedures can often be found in textbooks on natural resources assessments or software manuals (e.g. Lowell and Jaton, 2000; Eastman, 2009). In addition, some image processing and GIS software programs include tools to conduct LU change analysis, such as the low-cost and popular IDRISI (Eastman, 2009).

40. Table 4.4 is an example of a country level land cover change matrix. The vertical column indicates the year of the initial land cover image (2003). The duration of the period of change extends to 2006, as shown on the horizontal row. The diagonal of the table indicates unchanged land area units between 2003 and 2006 (in blue font).

41. Notice how these numbers are usually larger than most other numbers in the table. In most study areas, especially if the period of change is relatively short, the overall area of change is likely to be small. The figure in the first row and the second column indicates that

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[42] Using a raster GIS, the system automatically reduces the attribute table to unique combinations. Vector systems will need some kind of *dissolve* operation

[43] This procedure is often called DISSOLVE in database and GIS software packages. In the Peru analysis, 60 unique combinations of land use change were identified.

1.22 million ha changed from forest land in 2003 to cropland in 2006. Each cell in the land cover change matrix is read the same way. The total value at the end of the first row is the area in Forest in 2003 (93.60). The total value at the bottom of the first column is the total area in Forest in 2006 (98.46). Therefore the study area gained almost 5 million ha of forest between the two dates.

Table 4.4. A hypothetical land use change matrix.

		Change to **Land cover 2006**							
		FL	CL	GL	WL	SL	OL	ND	**Total**
Change from **Land cover 2003**	FL	89.11	1.22	1.64	0.47	0.02	0.45	0.69	**93.6**
	CL	0.87	45.28	1.09	0.30	0.35	0.39	0.18	**48.45**
	GL	1.79	1.27	14.73	0.49	0.03	0.21	0.15	**18.66**
	WL	1.22	0.65	0.58	7.78	0.03	0.30	0.01	**10.57**
	SL	0.03	0.17	0.04	0.01	2.61	0.02	0.01	**2.91**
	OL	0.20	0.28	0.32	0.11	0.02	2.09	0.01	**3.02**
	ND	5.25	1.50	1.03	0.20	0.04	0.17	2.51	**10.7**
	Total	**98.46**	**50.37**	**19.42**	**9.36**	**3.09**	**3.63**	**3.57**	**187.91**

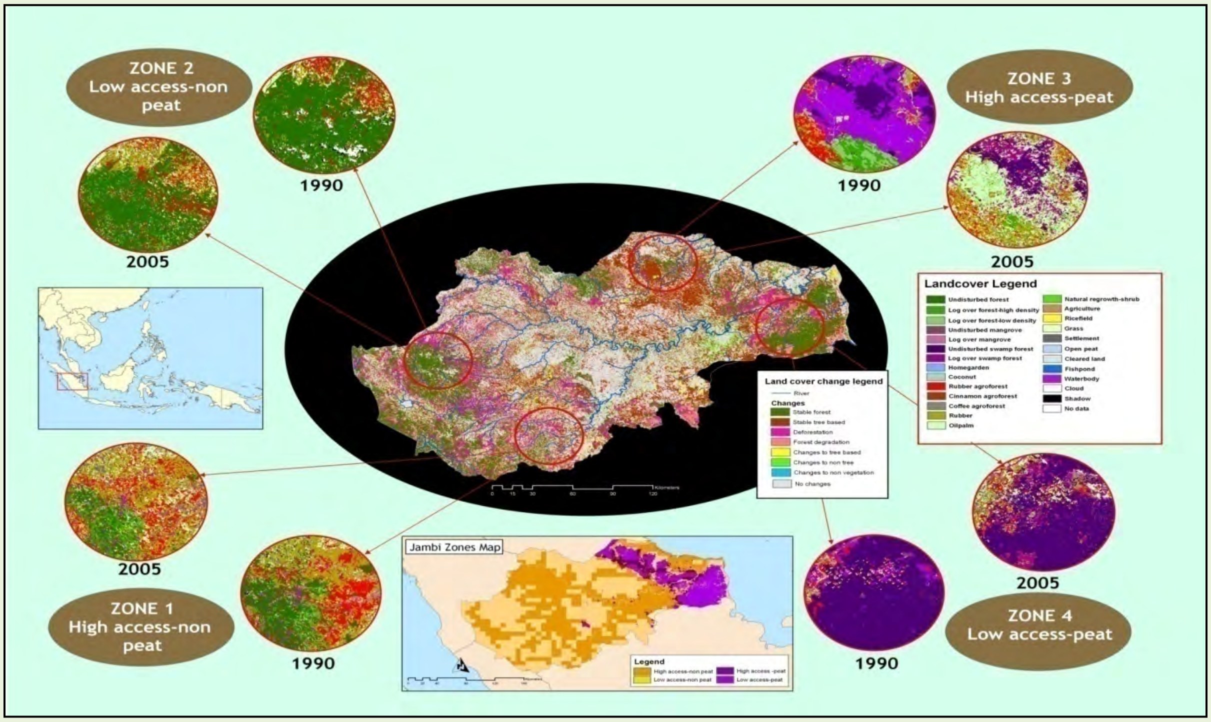
Land covers: FL= forest land, GL= grassland, WL= wetland, SL= settlement, OL= other land, ND= no data.
Source: Authors

42. The land use change matrix is a key input for the opportunity cost analysis spreadsheet. The matrix is copied directly into the spreadsheet where land use change information can be used with economic data to calculate opportunity costs.

43. The measurement of land use change, as described above, provides important data for opportunity cost analysis and for REDD+. In addition to providing data needed for the opportunity cost analysis, the land use change matrix can be used to assess the driving forces of deforestation and land use trajectories over time. The final section of this chapter below describes how to use land use change data in an effort to explain land use change.

Box 4.5. Land use maps for Jambi Province, Indonesia

Below is an example of land use maps derived from remote sensing in Indonesia (van Noordwijk et al., 2007). The study area has been zoned according to accessibility and the presence of peat soils, factors important in assessing the opportunity cost of avoided deforestation.



Land use maps for 1990 and 2005 in Jambi province, Indonesia

Source: van Noordwijk et al., 2007.

Explaining land use change

44. Land uses can change rapidly or slowly, sometimes for obvious reasons and sometimes because of hidden forces. Within a REDD+ context, understanding and explaining land use change is essential to both identifying appropriate emission level reductions and effective policies to maintain and increase carbon stocks.

45. Here we discuss three related topics, the *forest transitions, drivers of deforestation* and *land use trajectories*. Inquiry into forest transitions helps to identify the conditions of national forests: ranging from natural/pristine to logged and degraded. Forest condition has implications on carbon content, future profits and opportunity cost estimates. Analysis of the drivers of deforestation attempts to answer the question of why deforestation occurs. The topic of land use trajectories is based on analysis of past land use change. Understanding of forest condition, drivers of change and types of change are essential to identifying plausible future land use trajectories, from which REDD+ opportunity costs are estimated.

Forest transitions

46. The world's forests have experienced different levels of use. Given the condition of forests, specific components of REDD+ policy (with respect to deforestation, degradation, afforestation/reforestation) can be more relevant in some countries than others. To compare the status forests can be a transition curve can be used (Figure 4.4) that reflects the dynamics of agriculture, forests and other land uses over time (Angelsen, 2007). Consequently, the location of a country (or sub-national region) on the forest transition curve can affect the priorities for participating in REDD+ programs and associated opportunity costs. The forest transition framework uses four basic categories:

1) Countries with **low deforestation and high forest cover** such as the Congo Basin and Guyana. In these countries, forests are relatively undisturbed, however deforestation and degradation may increase in the future. Degradation is important since these countries are less likely to benefit from 'avoiding deforestation'.
2) Countries with **high deforestation** such as (areas of) Brazil, Indonesia and Ghana. These countries have strong incentives to engage in deforestation accounting. Nevertheless, they are less likely to have a significant interest in accounting for degradation unless little additional accounting effort is required.[44]

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[44] The exclusion of forest degradation from national REDD+ programs, especially where selective logging is common, could lead to considerable leakage.

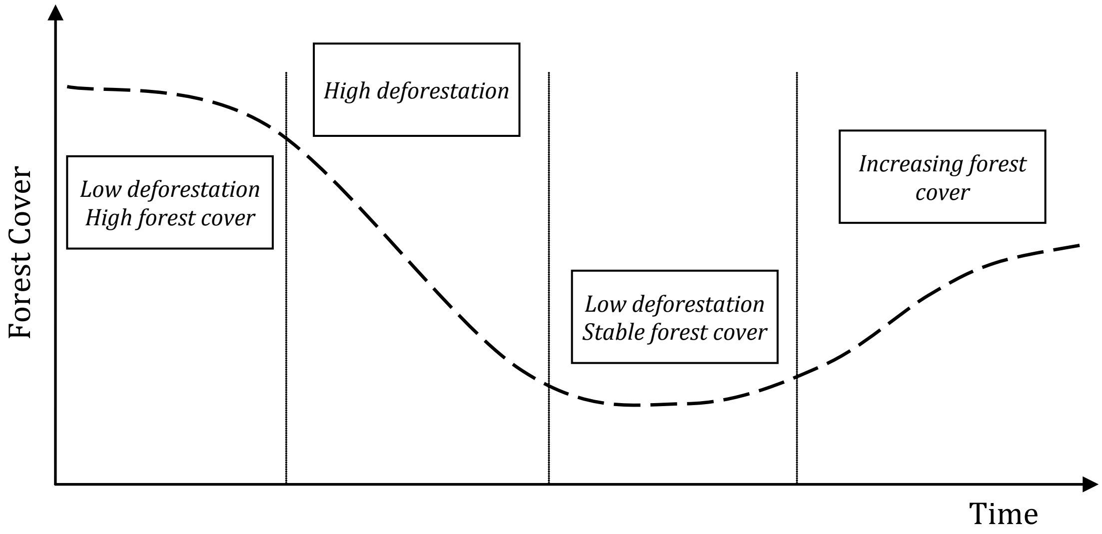


Figure 4.4. Categories of forest transition

Sources: Adapted from Angelsen (2007) and Murdiyarso (2008).

3) Countries with **low deforestation and stable forest cover** are characterized by forest mosaics and stabilized forests. Either because the forest has already been largely cleared or because of effective forest protection policies, deforestation rates have leveled off. India and parts of Central America may pertain to this category. These countries may be interested in reducing degradation, probably in combination with forest conservation, afforestation and reforestation, and other schemes aimed at enhancing forest carbon stocks.
4) Countries with **increasing forest cover** such as China and Vietnam. These countries have interest in degradation accounting and enhancing their carbon stocks. Although national forest area may be increasing through plantations, existing forests may be simultaneously experiencing degradation, which could be reverted through protection or enrichment plantings.

Driving forces of deforestation

47. Knowledge of the broader factors driving deforestation helps analysts understand the potentially complex causes of land use change, estimate both business-as-usual and reference emission levels, and identify appropriate policies required for achieving REDD+.

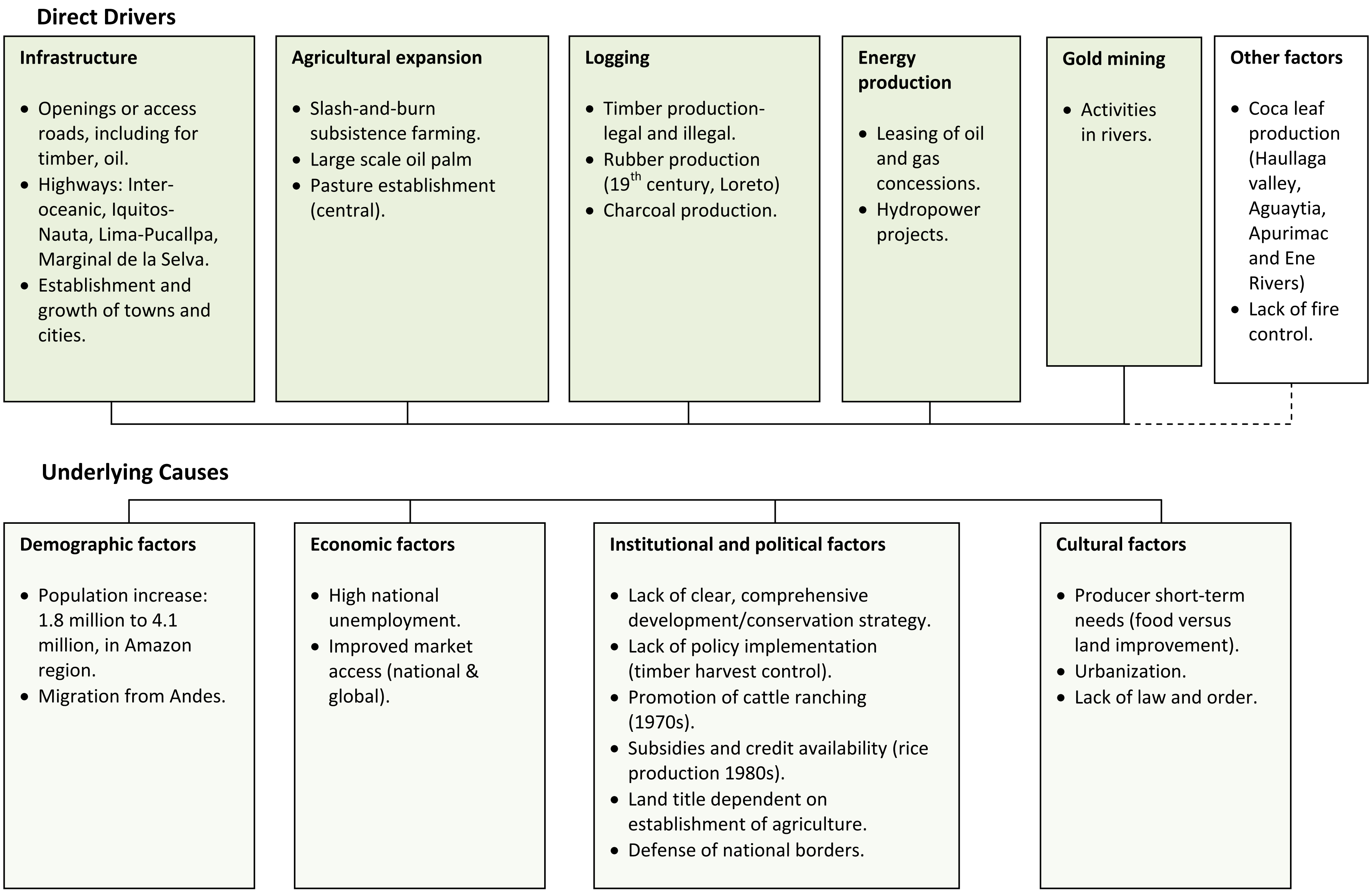
48. Causes of deforestation can be either observable or hidden (Meyer and Turner, 1992; Ojima, et al., 1994). A global meta-analysis of 152 sub-national case studies categorized deforestation across the tropics into three categories of observable causes: (1) agricultural expansion, (2) wood extraction, and (3) infrastructure extension (Geist and Lambin, 2001, Table 4.5). These causes are in turn influenced by underlying driving forces that are more difficult to assess. Such hidden driving forces typically act in conjunction with each other – at different temporal and spatial scales.

Table 4.5. A categorization of observable and hidden causes of deforestation

Observable causes		
Agricultural expansion	Staple food expansion (smallholder) Commercial agriculture (large-scale and smallholder)	
Wood extraction	Timber extraction	Private company logging Undeclared logging
	Fuelwood/charcoal	Domestic uses rural & urban Industrial uses
Infrastructure extension	Roads (public, logging)	
	Private enterprise infrastructure	Hydropower Mining Human settlements
Hidden causes		
Economic	Market growth	Demand growth in urban centers Increased accessibility to urban markets Changes in consumer diets (e.g. meat) Poverty Price shocks Missing or underperforming credit and input markets
Policy and institutional factors	Formal policies	Export taxation, price interventions (e.g., subsidies) Industrial policy Agricultural research and extension Migration policy Land reforms
	Open access to forest lands (Cote d'Ivoire, Ghana, Cameroon)	
Agricultural technology	Labor saving innovations Little or no generation of land saving innovations Technological stagnation leading to extensification	
Demographic	Population growth Migration Spatial population distribution	
Social triggers	Health & economic crisis conditions (e.g., epidemics, economic collapse) Government policy failures (e.g., abrupt shifts in macro-policies)	

Source: Geist and Lambin, 2001.

49. In Peru, for example, the national REDD+ team first reviewed the global literature on the drivers of deforestation (Velarde, et al., 2010). Next, existing national deforestation studies were reviewed. Based on these resources, an analysis framework was created with the direct and indirect drivers of deforestation in the Peruvian Amazon (Figure 4.5). While this information is not directly needed for opportunity cost calculations, the analysis enabled the national team to develop future scenarios of land use and estimate reference emission levels (RELs). This information can help to prioritize specific land uses for opportunity cost analysis.



Direct Drivers

Infrastructure

- Openings or access roads, including for timber, oil.
- Highways: Inter-oceanic, Iquitos-Nauta, Lima-Pucallpa, Marginal de la Selva.
- Establishment and growth of towns and cities.

Agricultural expansion

- Slash-and-burn subsistence farming.
- Large scale oil palm
- Pasture establishment (central).

Logging

- Timber production-legal and illegal.
- Rubber production (19th century, Loreto)
- Charcoal production.

Energy production

- Leasing of oil and gas concessions.
- Hydropower projects.

Gold mining

- Activities in rivers.

Other factors

- Coca leaf production (Haullaga valley, Aguaytia, Apurimac and Ene Rivers)
- Lack of fire control.

Underlying Causes

Demographic factors

- Population increase: 1.8 million to 4.1 million, in Amazon region.
- Migration from Andes.

Economic factors

- High national unemployment.
- Improved market access (national & global).

Institutional and political factors

- Lack of clear, comprehensive development/conservation strategy.
- Lack of policy implementation (timber harvest control).
- Promotion of cattle ranching (1970s).
- Subsidies and credit availability (rice production 1980s).
- Land title dependent on establishment of agriculture.
- Defense of national borders.

Cultural factors

- Producer short-term needs (food versus land improvement).
- Urbanization.
- Lack of law and order.

Figure 4.5. Direct and underlying causes of deforestation in the Peruvian Amazon

Source: Adapted from White, et al. (2005), Geist & Lambin (2002), Reducing Emissions from All Land Uses *project (REALU; Velarde, et al., 2010).*

Identifying land use trajectories

50. The term *land use change* can have different meanings, especially within a REDD+ context. Land use can imply a change from forest to agriculture, from one agricultural crop to another, or a series of land use changes. Therefore, clarification of what is meant by land use change is essential to REDD+ policy discussions and the estimation of opportunity costs.

51. Land use change is rarely a quick, one-time independent event, such as: natural forest to agricultural production. Especially in forest frontiers, lands typically undergo a series of inter-related changes over many years. An often-observed sequence begins when loggers enter a forest to selectively cut the highest value timber trees. Later, logging companies selectively cut other lower-value species. Next, pioneer settlers convert the remaining forest with slash-and-burn techniques into agricultural land parcels. After a few years of production, the parcel is left fallow for several years. Such swidden agricultural (crop-fallow) practices may continue, or the parcels may be converted to pastures for cattle or to intensive agriculture.

52. Analysis of land use histories within forest frontiers provides important indications of how land use would likely change without a REDD+ program. These future land use change scenarios are termed *land use trajectories*. Each of the land uses that comprise the changes have distinct carbon stocks and profit levels, and thus have an effect on REDD+ opportunity cost estimates.

53. The approach presented here integrates the whole sequence of changes, which takes into account land uses *during* and *after* forest conversion (e.g., from the initial forest to the end stage). This comprehensive approach of land use change enables countries to understand the current situation and estimate likely land uses in the future.

54. Identification of land use change is best achieved through collaborative discussions amongst local and external specialists. This dialogue can be advanced while identifying predominant land uses and the level of precision for the opportunity cost analysis (Tiers 1,2,3).

55. To guide a land use analysis of national level, five general types of land use change are identified. These changes are based on product (forest versus agricultural/ranching) and frequency of change within the analysis horizon: cyclical, direct or one-time and transitional. The five types are forest harvests, forest conversions, agricultural cycles, agricultural transitions and direct changes, and are depicted in Figure 4.6. Context of the analysis is provided by the forest and non-forest land uses before the analysis horizon.

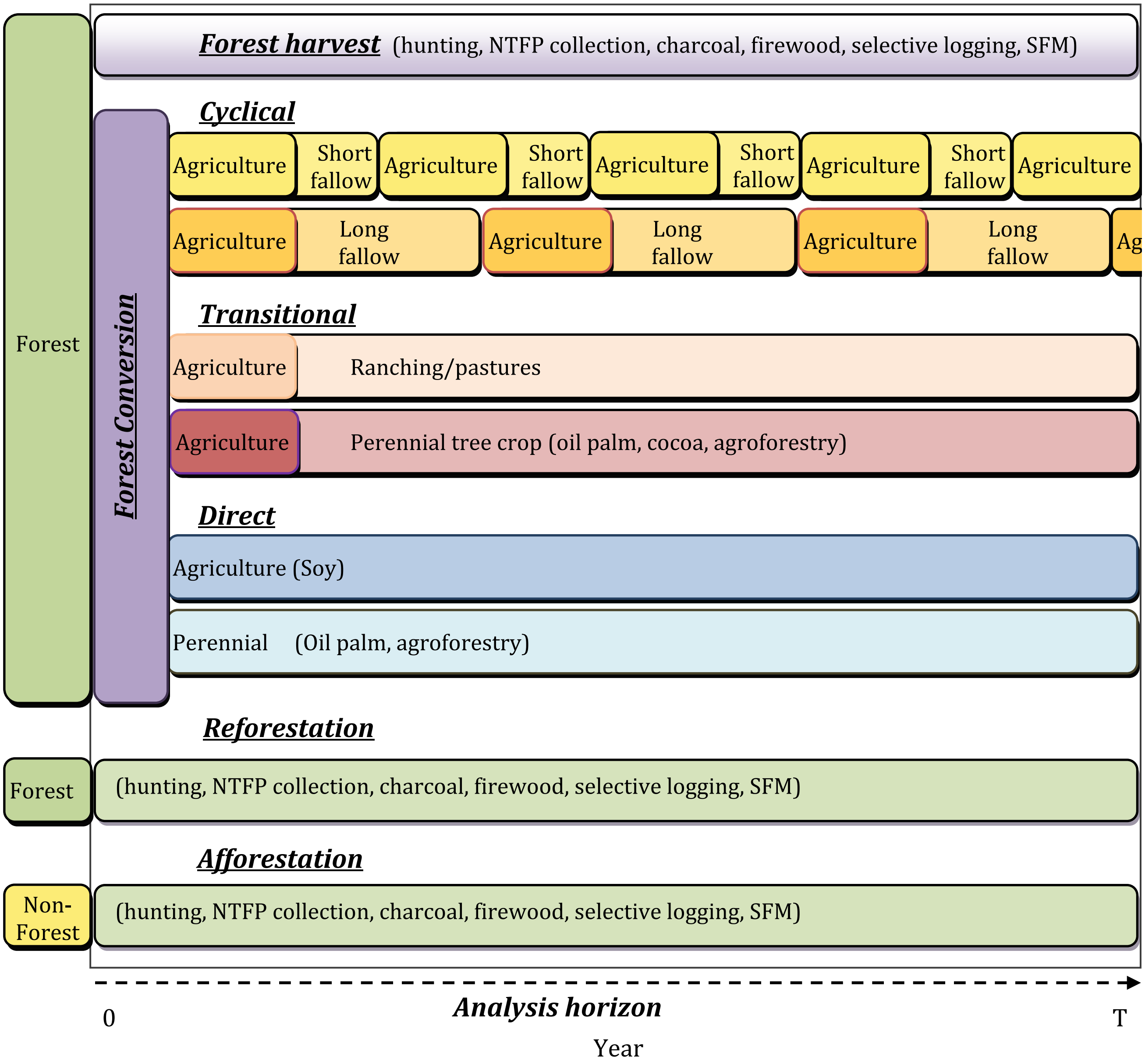


Figure 4.6. Land use change trajectories: types and examples

Source: Authors.

Forest harvests

56. Some human activities within forests can generate profits with little or no effect upon trees. Harvesting activities, such as hunting and some non-timber forest product collection (NTFP), can occur consistently throughout a time horizon and not affect a forest's carbon density levels. Other activities, such as logging or intensive fuelwood collection can significantly impact carbon. These activities change the forest from its natural state.

57. Even relatively invasive timber harvesting practices which have a great impacts upon a forest may not cause it to lose its land use categorization of forest. Recall that the broad

IPCC definition of forest enables somewhat substantial changes to occur (i.e. a reduction tree coverage or degradation).

58. Each of these forest harvest activities generates different products and profit, with different carbon impacts upon forests. Therefore, carbon and profitability estimates from forest land uses should consider a potentially broad array of different forest management and harvest practices, some of which occur a few times in a given period (e.g., timber harvests) and others that occur more frequently, perhaps annually (e.g., NTFP collection).

Forest conversion

59. Conversion from forest to other uses is a well-known type of land use change. This one-time change, however, can produce distinct financial results depending on the context. Trees can be a financial burden or a benefit during the conversion process. If sold for timber or charcoal, trees can generate substantial profits. In contrast, if tree products cannot be sold, then the cost of their removal can reduce profits.

60. Forests are not all the same. Many forests, especially in established frontier areas, have been partially harvested, with high-value timber already having been logged. REDD+ opportunity cost analysis requires recognizing the often-spatially determined factors of tree use (and profits). This wide range of potential financial impacts can greatly affect estimates of REDD+ opportunity costs. More on this topic in Chapter 6.

The next three land use changes primarily refer to agricultural and ranching activities.

Cyclical change

61. Cyclical land use change is a repetitive series of land uses, often called a land use system. An example of a cyclical change is an agricultural crop and fallow rotation. This cycle of land use typically repeats itself throughout a time horizon. Although specific crops within the cycles may differ, general patterns can be discerned that can simplify a profitability analysis.

Transitional change

62. Land use transitions are changes that do not repeat over time. A common transition is slash-and-burn agriculture to perennial land uses, such as tree crop or cattle systems. The new enterprise activity typically replaces the fallow phase, rather than continuing a crop-fallow cycle. Substantial investments of capital and labor are often needed before the new land uses generate positive earnings.

Direct change

63. In some forest margin areas, lands are directly converted from forest to agricultural or tree production. Often led by large multinational firms, soy, agroforestry systems or oil palm plantations are examples of direct changes.

The following land use changes refer to the "+" in REDD+.

Reforestation

64. Reforestation refers to the replanting of a cleared or partially cleared forest (i.e. degraded forest). Numerous types of livelihood activities can occur with established forests.

Afforestation

65. Growing new forests is termed afforestation. Such an activity typically occurs where forests did not exist or were present many years ago.

Predicting land use change

66. Future projections of land use change are an important component in estimating baseline and reference emission levels. Figure 4.7 shows how analysis of historical trends link with future projections.

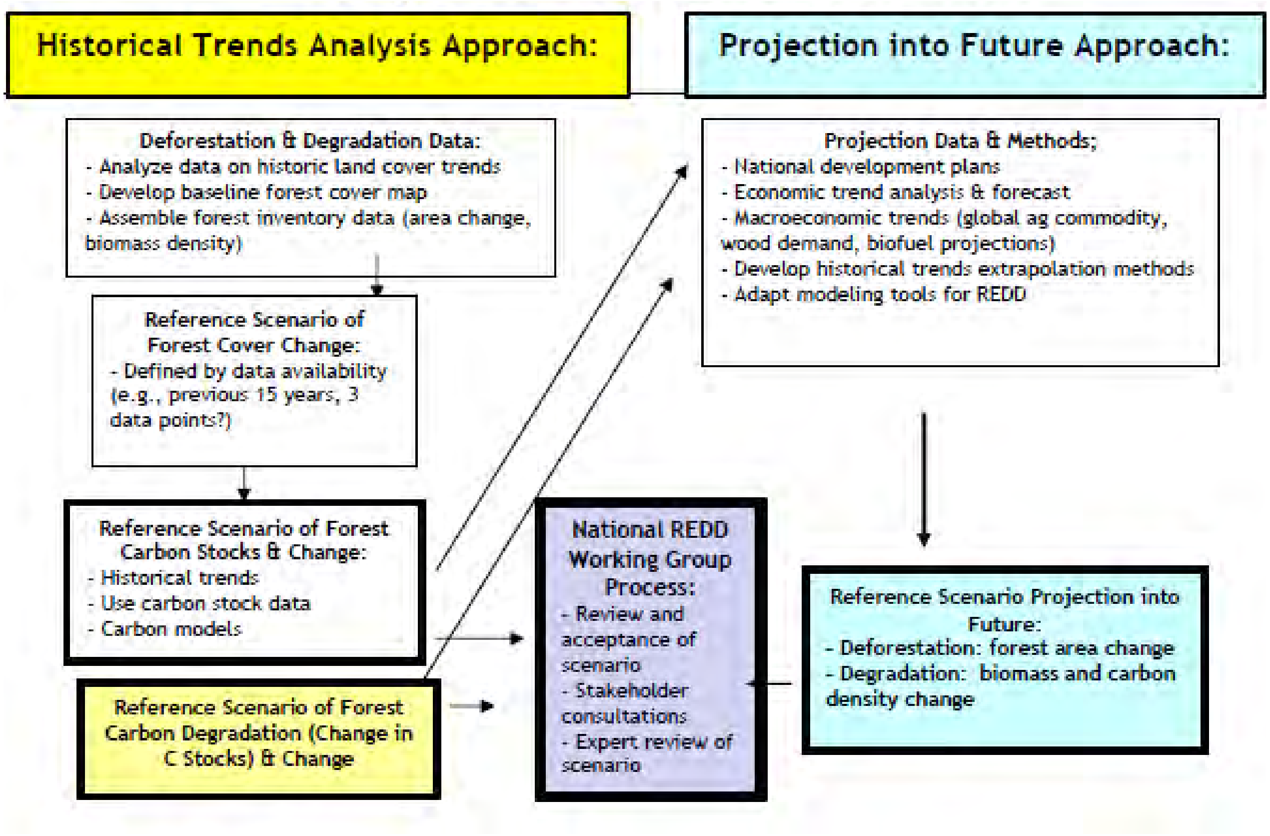


Figure 4.7. Land use change: links between historical and future analyses

Source: FCPF, 2010.

67. Analyses of future land use change range from simple to sophisticated. Simple approaches include extrapolating past land use change into the future. Adjustments can be made to account for both bio-physical (e.g., soil fertility, road access, etc.) and socio-economic factors (e.g., population growth, government development policy, food prices, etc. Sophisticated approaches include spatial probabilistic analyses with different explanatory variables and feedback effects. See Agarwal, et al. (2002) for an extensive review of land use change models. Despite the wide range of complex analytical methods, scenario analyses are important to compare the effect of different data, contextual and method assumptions.

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