

Reference scenarios for deforestation and forest degradation in support of REDD: a review of data and methods

Lydia P Olander¹, Holly K Gibbs², Marc Steininger³,
Jennifer J Swenson⁴ and Brian C Murray¹

¹ Nicholas Institute for Environmental Policy Solutions, Duke University, USA

² Center for Sustainability and the Global Environment (SAGE) Institute for Environmental Studies, University of Wisconsin-Madison, USA

³ Center for Applied Biodiversity Science, Conservation International, USA

⁴ Nicholas School for the Environment and Earth Sciences, Duke University, USA

Received 1 August 2007

Accepted for publication 9 May 2008

Published 11 June 2008

Online at stacks.iop.org/ERL/3/025011

Abstract

Global climate policy initiatives are now being proposed to compensate tropical forest nations for reducing carbon emissions from deforestation and forest degradation (REDD). These proposals have the potential to include developing countries more actively in international greenhouse gas mitigation and to address a substantial share of the world's emissions which come from tropical deforestation. For such a policy to be viable it must have a credible benchmark against which emissions reduction can be calculated. This benchmark, sometimes termed a baseline or reference emissions scenario, can be based directly on historical emissions or can use historical emissions as input for business as usual projections. Here, we review existing data and methods that could be used to measure historical deforestation and forest degradation reference scenarios including FAO (Food and Agricultural Organization of the United Nations) national statistics and various remote sensing sources. The freely available and corrected global Landsat imagery for 1990, 2000 and soon to come for 2005 may be the best primary data source for most developing countries with other coarser resolution high frequency or radar data as a valuable complement for addressing problems with cloud cover and for distinguishing larger scale degradation. While sampling of imagery has been effectively useful for pan-tropical and continental estimates of deforestation, wall-to-wall (or full coverage) allows more detailed assessments for measuring national-level reference emissions. It is possible to measure historical deforestation with sufficient certainty for determining reference emissions, but there must be continued calls at the international level for making high-resolution imagery available, and for financial and technical assistance to help countries determine credible reference scenarios. The data available for past years may not be sufficient for assessing all forms of forest degradation, but new data sources will have greater potential in 2007 and after. This paper focuses only on the methods for measuring changes in forest area, but this information must be coupled with estimates of change in forest carbon stocks in order to quantify emissions from deforestation and forest degradation.

Keywords: tropical deforestation, carbon emissions, UNFCCC, REDD, climate policy, avoided deforestation, forest, remote sensing, baseline

1. Introduction

Deforestation and forest degradation in the tropics currently account for about 20% of global greenhouse gas (GHG)

emissions and constitute the majority of emissions from developing countries (IPCC 2007, Gullison *et al* 2007). In addition to their critical role in the global carbon cycle and climate system, tropical forests are home to about half of the

world's species and provide a livelihood for millions of people. Recognizing the importance of tropical forests and the value of developing country participation in global climate change mitigation efforts, proposals are now being rapidly advanced to compensate tropical forest countries for Reducing Emissions from Deforestation and Degradation, or REDD, as part of a future international climate agreement (UNFCCC Country submissions 2007; Olander and Murray 2007, Gullison *et al* 2007). At the United Nations Framework Convention on Climate Change Conference of the Parties that took place in Bali in December of 2007, the parties agreed that reduced emissions from deforestation would be included in the post-2012 agreements (UNFCCC, COP 13 Report, 2008). At this meeting the discussion about using a national reference scenario to assess rewards for avoided deforestation exposed the complexity and political nature of this issue (Zwick 2007). In this paper we discuss a range of data sources and methods available to estimate national reference scenarios.

REDD measurements will likely be based on the carefully crafted and negotiated methodologies for land use, land-use change and forestry (LULUCF) under the UNFCCC, which are the 2003 and 2006 The Good Practices Guidance (GPG) for Land Use, Land-Use Change, and Forestry and the Revised 1996 Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories. The measurement system set up in the GPGs uses three tiers that range from coarse resolution data using general equations to substantially refined local data used in sophisticated models. The benefits of using these methods as the basis for REDD are: (1) they have been developed and reviewed by experts (2) they have already been accepted in UNFCCC negotiations, (3) they have been tested over the initial phase of the Kyoto Protocol and (4) a tiered system provides flexibility for differences in technical capability among countries. The existing methods cover all types of land-use changes and transitions and account for both carbon emissions and sequestration, while the REDD system currently under discussion focuses only on emissions from deforestation and forest degradation (Milne and Jallow 1996).

For measuring REDD, countries will need to know: (1) the aerial extent of deforestation and forest degradation (hectares), (2) for degradation, the proportion of forest biomass lost (percentage), (3) where the deforestation or forest degradation occurred (which forest type), (4) the carbon content of each forest type (metric tons of carbon per hectare), and (5) the process of forest loss which affects the rate and timing of emissions (Ramankutty *et al* 2007). Ultimately, the quantities of interest are units of carbon emissions avoided by reducing deforestation and forest degradation. This paper focuses on the measurement of historical forest area change, while another paper in this issue addresses quantification of forest biomass carbon stocks (Gibbs *et al* 2007). To quantify emissions it is critical that the methods for quantifying land cover change discussed herein can be effectively linked to carbon stock and flux estimates.

Measuring a reduction in emissions from deforestation and forest degradation raises the question of what the reduction is compared to. The terms 'baseline' or 'reference scenario' refer to a situation without a particular policy in place, either

before the policy was enacted, or a prediction of what would have happened without the policy in place. In the case of REDD, reduction in emissions from deforestation and forest degradation below the baseline or reference scenario could be considered additional and eligible for compensation. For example: if the reference scenario emission from deforestation for country X is 20 000 metric tons of carbon per year and these were then reduced to 18 000 metric tons, the country could receive compensation for 2000 metric tons.

Measuring and monitoring of forest change in the coming years will be able to take advantage of emerging remote sensing technology but reference scenarios, which are heavily based on historical trends, will depend largely on existing data. In this paper we review existing data and methods to estimate deforestation and degradation reference scenarios and highlight some key challenges.

2. Defining deforestation and forest degradation for measurement

Clear measurable definitions of deforestation and forest degradation are essential. Current definitions may not be appropriate depending on the assessment method used. In the REDD context, deforestation has been defined as a 'measurable sustained decrease in crown cover' below a 10–30% threshold (UNFCCC 2006). Deforestation defined in this manner may be difficult to measure using available data. With existing inventories and remote sensing it will not always be possible to accurately estimate per cent canopy cover across a country and the different forest types and terrain that it encompasses. For example, degradation, defined as a loss of biomass density without a change in the area of forest cover (i.e. decrease in crown cover that does not fall below the 10–30% threshold), is even more challenging to measure.

Specific measurement definitions may need to be developed guided by the policy goals, available data, and methods reasonably attainable by the countries. The IPCC Good Practice Guidelines contain some important rules of thumb: '... land should be categorized in such a way that is reasonably consistent with IPCC guidelines⁵, robust for carbon estimates, mappable by remote sensing, and inclusive of all land area to reduce error.' (Milne and Jallow 1996). Mappable by remote sensing is key for tropical nations because most lack reliable inventory data.

3. A framework for estimating baselines or reference emissions scenarios

For REDD the reference emissions scenario under discussion is a national-level trend based on or projected from historical trends in emissions from forest change (UNFCCC Country submissions, 2007; Olander and Murray 2007). These trends should be measured over multiple years (5–10) in order to reduce the impact of anomalous years. The reference period selected will likely be determined in negotiations, but a more

⁵ So that it aligns with activities already being accounted for like those in CDM.

recent reference period (in the last 5–10 years) may better reflect current land-use trends and be most feasible given constraints in available data.

Because emission reductions from deforestation and forest degradation would be matched by financial compensation, a credible method for measurement is absolutely essential. Historical reference trends should have the following characteristics.

Accuracy and precision. All reasonable efforts should be made to ensure that estimated changes in forest cover and greenhouse gas fluxes closely reflect what is happening on the ground. The measurement error or uncertainty need to be quantified to determine how much confidence can be placed in REDD credits. Uncertainty is unavoidable and will vary by country. The uncertainty could be used to qualify the REDD values—a discounting or grading system could adjust the values for REDD credits accordingly.

Comprehensiveness. The reference scenario should cover all relevant activities. For instance, if all deforestation in the country is to be included, then all sources of deforestation in a country must be represented by the data used to develop the reference scenario estimate. If degradation is to be included, then the data need to have high enough resolution to quantify the amount of area degraded.

Environmental integrity. For the REDD system to work in favor of climate protection, it must ensure that the corresponding greenhouse gas reductions are real. Given the various forms of uncertainty described herein, prudence suggests that reference scenarios be set conservatively (not too high) as a safeguard against rewarding too much REDD credit and diminishing global greenhouse gas mitigation efforts.

Transparency. Minimum standards of transparency will aid in the verification and ensure fairness and integrity of the REDD system; this includes documentation of data and methods and making them available to third parties.

Flexibility. A wide range of circumstances—including differences in data availability, dominant type of land use, terrain, and the capacity to incorporate remote sensing methods—will apply across and within countries affecting their ability to estimate reference scenarios. A REDD system will need to be flexible in allowing and accounting for variability in methodologies and accuracy.

Feasibility. The proposed approaches for estimating reference scenarios must be possible with a reasonable level of effort and expense or else they will simply not be done well or done at all. Feasibility factors include data availability, analytical capabilities, cost of data collection and analysis, and institutional support for these efforts.

Compatible. The proposed methods to estimate deforestation and forest degradation must be compatible with methods used to estimate forest carbon stocks. Definitions of deforestation and forest degradation must also be measurable using available data and methods.

4. Data options for measuring historical forest change

The data needed for measuring forest change for a historical reference period must have national coverage and enable an

acceptable error for a minimum of two time points (likely 5–10 years apart). Because deforestation is often in the form of many small patches of clearings, resolutions of less than 100 m are recommended in most cases. The FAO estimates deforestation using national statistics for all countries, and while the data are available freely, they are of mixed quality. In many cases a better alternative may be remote sensing data. The following sections will describe these data options in more detail.

4.1. FAO national statistics

The FAO has been conducting global forest assessments every five to ten years since the first survey in 1947. National statistics are largely based on forest inventory data, models, and expert opinion (FAO 2001). The national statistics provide estimates of forest area and net deforestation rates by country for 1990, 2000, and 2005 (FAO 2006). While valuable for their coverage over time and in-country capacity building, the FAO data have been criticized for their lack of consistency between countries and between assessments—including changing definitions of forest, different methods to assess deforestation, and for unreliable and missing data in some cases (Grainger 1996, Matthews 2001). Further, the published country-level estimates provide no detail on degradation and are difficult to validate.

4.2. Remote sensing data

Remote sensing instruments mounted on satellites provide images of the Earth's surface and its forest cover starting as far back as the 1970s and are generally the most reliable data source for accurately estimating changes in forest over large areas. However, remote sensing imagery can be expensive and technically challenging to analyze, and the error and uncertainty in the data and analyses are not always well characterized.

Numerous satellites sensors that can be used to detect land cover change have been launched by India, Brazil, Australia, Nigeria, Canada, the EU (and many of its member nations), the United States, and Japan. See table 1 for an overview assessment of the data types and their benefits and limitations. NASA's Geocover project has released global coverage of Landsat images for circa 1975, 1990 and 2000, and soon 2005. At the time of writing, this is the best option for low-cost, quality satellite data (Tucker *et al* 2004). By the beginning of 2009, the entire collection of historic and current Landsat imagery will be made free to the public (USGS 2008). Data from other satellite sensors can be used to fill gaps from cloud cover in the Landsat database, to help assess forest degradation, and to validate and determine the uncertainty in the Landsat measurement.

Data options for 1980s and 1990s

Landsat and AVHRR (Advanced Very High Resolution Radiometer) are the only satellite data options for estimating forest change reference scenarios for the 1980s and 1990s. The daily coverage and long-term record are major advantages of AVHRR data. However, the coarse resolution of this

Table 1. Types of remote sensing data that can be used for measuring reference scenario forest change.

Data type	Scale	Benefits	Limitations	Costs
Optical	Coarse Resolution (e.g. AVHRR, MODIS, SPOT-VEGETATION) For Example: ~1 km resolution ~2300 km Image width ~ Daily frequency	— Image processing can be automated and completed quickly for rapid assessment — Daily coverage helps overcome issues of cloud cover	— Small areas of forest change (i.e. small-scale agriculture) likely missed biasing estimates of deforestation — Unlikely to detect forest degradation	Free to low cost
	Moderate to high resolution (e.g. Landsat, SPOT HRV, ASTER, IRS, CBERS) For example: ~30 m resolution ~180 km Image width ~ Biweekly frequency	— Possible to conduct regional/country scale assessments — Possible to detect some types of degradation — Global pre-processed landsat available	— Smaller area covered per image, thus slower and more expensive to fully cover a region — Cloud coverage is a problem, especially in humid tropics	Free to moderate cost
	High resolution (e.g., IKONOS, Quickbird) For example: ~4 m resolution ~11 km Image width	— Excellent validation of large-scale assessments — Possible to detect degradation — Good for validation	— Covers very small areas — Country coverage not available — Demanding to process — Only collects targeted or tasked locations	Expensive — must be tasked
Radar	Radar (e.g. ERS, JERS, Radarsat, ALOS PALSAR) For example: ~30 m resolution ~75 m image width	— RADAR signal penetrates through cloud cover — Existing data may be able to enhance other data options, but not sufficient by itself	— Requires high level of expertise — May not work well in mountainous regions	Free to expensive
Aerial photography	For example: variable high resolution ~10 cm to 1 m	— Good for validation of forest change and degradation	— Usually not large areas covered — Requires time and expertise	Moderate

data will miss much of the medium to smaller scale disturbances. In addition sensor degradation, inter-sensor calibration problems, geo-location errors, and noisy pixels limit AVHRR to identifying large-scale deforestation or rough, initial estimates of forest change (Agbu and James 1994). Hansen and DeFries (2004) concluded that AVHRR data likely result in a systematic bias underestimating deforestation. Thus, the best option during this period is data from the Landsat series of satellites, which provide an imagery archive of good quality starting in 1972. Landsat imagery has been used to identify forest clearings as small as 1 hectare or sometimes less in size (Steininger *et al* 2001, Leimgruber *et al* 2005).

Data options for late 1990s and 2000s

Due to its higher resolution, excellent archive and low cost, Landsat still provides the most viable data option for REDD, but Landsat 7 (most recent satellite) has experienced technical difficulties since 2003 that create linear gaps in the images⁶. However, corrections can be applied to the Landsat 7 imagery, using data from multiple satellite overpasses, to enable forest monitoring. For example, Hansen *et al* (2008a) describe an automated approach to filling gaps via processing many

Landsat scenes. The older Landsat 5 satellite has continued to collect imagery up through most of 2007, but data acquisition was temporarily suspended. Landsat-5 is working long past its expected service time, and there is no guarantee that it will last much longer. In addition, some regions do not have Landsat-5 receiving stations and thus there are no images available⁷. Imagery from other moderate to high resolution (e.g. ASTER, CBERS) sensors that came on line in the late 1990s might be needed supplement the Landsat data (reviewed in DeFries *et al* 2005, DeFries *et al* 2006).

The coarser resolution imagery from MODIS and SPOT-VEGETATION provide global coverage for the current decade. As is the case with AVHRR data, these data are best for less precise and more frequent measurements. They are helpful for finding and assessing areas with the greatest rates of change and for filling in temporal and spatial gaps where the higher resolution data is unavailable or insufficient (Achard *et al* 2007). This data can be very helpful for cloudy regions, seasonal forests, and measuring gradual degradation processes occurring at large scales (Hansen *et al* 2008a). For seasonal forests it may be necessary to have imagery for certain times of year (wet season) or for multiple seasons during a year to

⁶ On April 2003 the failure of the Landsat 7 ETM+ scan line corrector resulted in data gaps outside of the central portion of acquired images, seriously compromising data quality.

⁷ Regions not covered by any of the 12 International Ground Stations receiving Landsat 5 data as of March 2006, according to the USGS Landsat Missions website: http://landsat.usgs.gov/about_ground_stations.php

distinguish degradation and management from normal seasonal variability.

Several RADAR data options exist for this time period. The largest archive exists for the Japanese Earth Resources Satellite (JERS). JERS data have a resolution of up to 10, and 100 m-resolution mosaics have been produced for the much of tropical America, Africa and mainland Asia (GRFM 2008). All satellite RADAR data options during the 1990s have only one band and one polarization of data recorded, thus providing limited data dimensionality for classification algorithms. Since then, there are additional RADAR data sources, the most useful being from the Advance Land Observing Satellite (ALOS) sensor (EORC 2008).

In January 2006 Japan launched ALOS. It provides significant improvements for detecting land-use change. This satellite has a combination of sensors including fairly high resolution optical sensors and the most advanced radar sensor available for civilian use. It collects global terrestrial imagery every year at 10, 20 and 100 m resolution. This sensor can see through clouds, and smoke and haze from fires, and into the forest canopy. Full pan-tropical data are available for 2007 and initial demonstrations were done for regions in the Amazon, Western Africa and Southeast Asia (Rosenqvist *et al* 2007). RADAR data may be less useful in areas of significant terrain; however, they are certainly a valuable data source for very cloudy areas.

Landsat data for 1980–2005 which are available now

NASA has made global Landsat data for ~1975, ~1990 and ~2000 freely available⁸ (Tucker *et al* 2004). These data provide imagery for measuring historical rates of deforestation over the last two decades. These Landsat images are available now as global mosaics that have already been orthorectified and merged together. They are also available as the unprocessed individual Landsat scenes that comprise the global mosaics. The original scenes are better for image analysis than the mosaics.

Clouds obscure significant areas in imagery for the very humid or coastal tropics, which can be the areas with the greatest forest cover for some countries. To find imagery with the least cloud cover, images from different years are used. For example, examining the imagery for Ecuador that was used in the 1990 global Landsat mosaic, one image is from 1987, and the image that covers this same location in the 2000 mosaic is from 2001 (table 2). For this image location we are measuring a 14 year reference period using the images in the mosaics, instead of the expected 10 in order to get least cloudy data. For Ecuador, individual images range from 1999 to 2001 for the 2000 mosaic, and from 1986 to 1991 for the 1990 mosaic. By saving the information on image dates, correct rates can be estimated over the time period despite varying image dates.

Clouds cover portions of many images in the humid regions even when images are selected from a range of dates to avoid clouds. For example, the imagery metadata for Ecuador show that 2 to 3 images used in each of the mosaics has more than 30% cloud cover (table 3). It will be impossible

Table 2. Dates and estimated cloud cover for Landsat images for Ecuador that were used in the 1990 and 2000 mosaics (MDA federal 2004).

Image Path\row	1990 Mosaic Image date	Cloud Cover %	2000 Mosaic Image date	Cloud cover %
08\060	12-22-1989	0	08-30-2000	0
08\061	12-22-1989	0	08-30-2000	9
09\060	08-07-1989	0–10 ^a	09-09-2001	13
09\061	08-23-1989	0–10 ^a	09-11-2000	22
09\062	09-11-1987	0–10 ^a	08-10-1999	0
10\060	03-23-1986	50–60	11-14-1999	30
10\061	03-26-1987	10–20	09-16-2001	40
10\062	03-26-1987	0–10 ^a	05-11-2001	40
10\063	02-11-1986	0–10 ^a	10-31-2000	10
11\060	03-14-1986	40–50	03-31-2001	16
11\061	02-21-1990	20–30	11-23-2000	0
11\062	04-29-1991	0	11-23-2000	0

(Data is pulled from the original single image metadata.) ^a Visual estimates suggest that these images all had a least 5% cloud cover.

to determine a reference trend in forest cover change for regions that have cloud cover on either end point (impossible to determine if there was a change). Overlaying the 1990 and 2000 mosaics for the northwest portion of Ecuador, which is typical of a troublesome cloudy spot, we found that only 44% of the area was cloud free (figure 1). That means 1364 029 ha of forest are not accounted for in this region because of clouds.

Large data gaps caused by clouds will need to be filled with other sensor data, such as frequently acquired coarse resolution spectral (e.g., MODIS, or SPOT-VEGETATION) or radar data (e.g., JERS, ALOS, ERS or Radarsat), which may increase the costs of analysis and imagery (in the case of radar data) particularly for countries with continuous cloud cover (Hansen *et al* 2008b). Where possible, maintaining a consistent resolution is preferable to merging with significantly coarser resolution data.

The final issue to be aware of when using the mosaic data is the range of seasons in which the images were captured. The images for Ecuador range throughout the year (table 3). While this is not so critical for a consistently wet tropical forest region like Ecuador, it becomes much more important in countries with areas covered by seasonal forests.

Despite these considerations, freely available Landsat imagery used in the periodic global mosaics is the best single-sensor source data set available for providing a spatially explicit and transparent assessment of changes in forest cover in the short term. If these data are supplemented with other remote sensing data and ground inventories over the next few years, they can provide a robust data source for historical reference scenarios.

5. Methods for using remote sensing to measure forest change

To detect a change in forest cover (deforestation or forest degradation) with existing data, images are needed for two or more time periods. By overlaying the images and determining the differences between them, the change between the two dates can be determined. This multi-temporal data set can then

⁸ <http://glcf.umiacs.umd.edu/data/mosaic/>

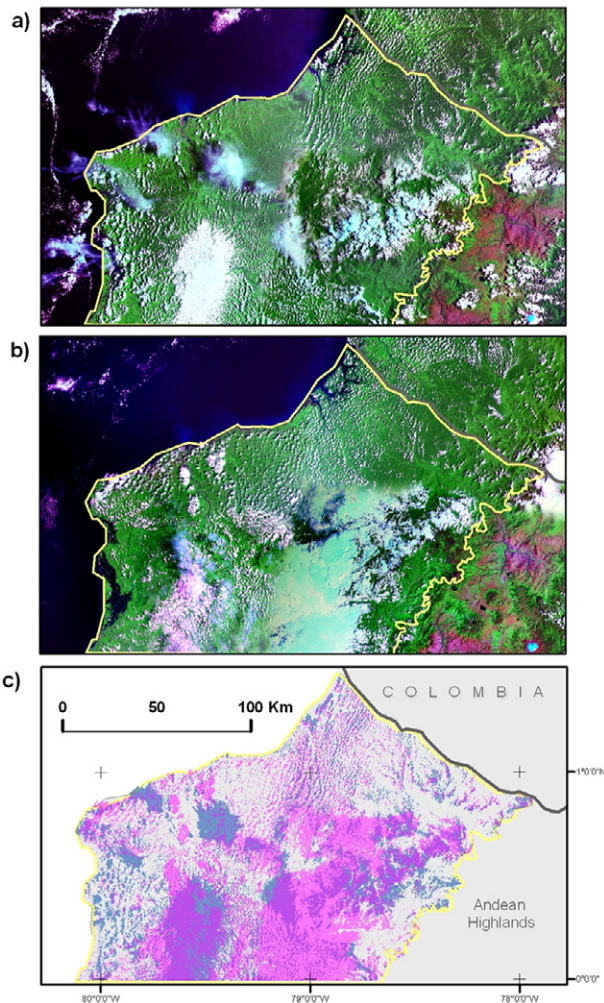


Figure 1. Landsat GeoCover Mosaic data for Northern Ecuador for (a) 1990, (b) 2000, and (c) cloud cover for both images overlaid.

be classified to show loss of forest, degradation of forest and other changes.

The two major approaches used to assess deforestation over large scales are ‘wall-to-wall’ and sampling methods. In wall-to-wall methods, images covering an entire country or region are analyzed. Sampling approaches use systematic sampling where a regularly spaced grid to identify plot locations across an entire region (Mayaux *et al* 2005) or random sampling stratified by topography, soil type, broad forest type, or degree of disturbance (hot spots) (FAO 2001; Achard *et al* 2002). Wall-to-wall mapping has primarily been used for sub-national or national-level assessments while sampling approaches have primarily been used for continental or global scale assessments.

A major motivation for using a sampling approach is to reduce costs and time associated with processing wall-to-wall imagery. While the sampling proposed by the FAO for continental estimates for the FRA2010 (DeFries *et al* 2007) would be sufficient for continental and global assessments, it is not sufficient for most national-level assessments (Tucker and Townshend 2000; Czaplewski 2003). Another concern about sampling is that any stratified sampling for the reference

scenario may constrain future monitoring so that it must be consistent with the originally selected stratification. If considering sampling for monitoring, a country should assess the potential sampling and classification errors expected from such an approach.

5.1. Accuracy in deforestation measurement

For an individual Landsat scene or local area, forest versus non-forest determination can have an accuracy of 90% to 95% (Roy *et al* 1991, Sader *et al* 1989, Steininger 1996). Patches of forest clearing of around 1.0 ha can be detected. At the national level with variation in topography and forest type across the landscape, accuracies can be a bit lower, ranging from 85% to 90% (e.g. Steininger *et al* 2001, Leimgruber *et al* 2005). The minimum patch size usually detected at the national scale is around 2–5 hectares. For coarser resolution forest cover change detection using MODIS data, recent modeling approaches in the tropics produced errors as low as 7–11% for annual changes at 250 and 500 m resolution (Hayes and Cohen 2007, Hayes *et al* 2008).

For validation or accuracy assessment of a given image, much finer resolution satellite or ground-based inventory data must be obtained. For images created from moderate to coarse-scale remotely sensed data (e.g. Landsat, MODIS) this would consist of field surveys or high resolution aerial photos or imagery. For many countries, conducting national ground surveys of current deforestation extent is not feasible. Aerial photos, traditionally used as a source for remote assessments, have become more accessible with the advent of digital cameras or airborne videography, though still remains expensive. High-resolution imagery such as IKONOS or QuickBird is costly and only covers a small land extent. An excellent source of free viewable data, where available, is the high-resolution imagery from Google Earth. The imagery is continuously updated and improved to higher resolutions (as fine as 50 cm), and is available across many portions of the world. While the imagery cannot be fully linked into image processing packages, it has great potential for map validation in some areas by combining visual interpretation with GIS polygon and point files that can be imported and overlain in Google Earth.

5.2. Accuracy in degradation and managed forest measurement

Measuring the extent of forest degradation and forest management is much more difficult than measuring deforestation (DeFries *et al* 2007). There are a range of canopy densities and ecosystem types across the tropics. This natural variation in forest cover can be due to underlying biophysical elements (e.g. semi-xeric, semi-deciduous, shrublands, limiting soil conditions such as the white sand forests of the Amazon). To many satellite sensors these ecosystems appear similar to degraded areas of neighboring forest. Human intervention in these more open canopies is very difficult to distinguish. This type of confusion could be alleviated to a degree by having an accurate and detailed vegetation map of these various natural canopy types (e.g. Josse *et al* 2007, Navarro and Ferreira 2007), something

that many rainforest nations lack. Rapid forest growth in moist tropical areas can lead to a perceived dense forest cover, a few years after selective logging or in a forest made up of low density early successional species. These perceived 'intact' forests have less biomass and thus their deforestation or forest degradation will result in lower carbon emissions than a truly 'intact' forest.

An ideal way to identify degradation is to analyze annual time series of Landsat imagery to see the transitions. Unfortunately this is very difficult to do with existing data because high-resolution imagery like Landsat is not recorded frequently enough to provide the needed cloud-free imagery (Asner 2001). Even light clouds or haze over tropical forests can be a problem because it is often confused with degraded forests during satellite image classification. Coarse resolution imagery (e.g., MODIS) has sufficient temporal frequency for a time series (ideally multiple images per year to distinguish degradation from effects of seasonality). However, at coarse resolution much forest degradation, which is often small scale, can be missed.

It is even more difficult to determine the carbon emissions to assign to different types and degrees of forest degradation and the accuracies of such an effort, but efforts are underway to improve this (Gibbs *et al* 2007). It seems plausible that degradation be included in a REDD system but would only be credited in countries that can demonstrate credible measurements with clearly determined uncertainty. This may be more difficult to do, but worth it for countries where forest degradation is a major source of emissions.

6. Existing analyses of deforestation using remote sensing

A number of pan-tropical or country-level analyses of deforestation have been done using remote sensing data. We will briefly discuss some of the main efforts and their limitations for developing national-level reference scenarios.

6.1. Sampling approaches

The FAO conducted a remote sensing analysis by sampling Landsat data stratified by broad forest types to estimate deforestation in the 1980s and 1990s (FAO 2001). The Landsat scenes were classified visually and included a number of different land cover types from which it may be possible to distinguish degradation in addition to deforestation. This was a pan-tropical analysis and the sample size was sufficient only for continental-level estimates. A more intensive sampling scheme would be necessary for national-level analysis (Tucker and Townshend 2000, Czaplewski 2003).

The European Union's Joint Research Center in its most recent global assessment used coarse resolution satellite data from 1990–1997 to create a base map upon which experts selected regions of greatest deforestation, 'hot spots', across the tropics (Achard *et al* 2002, Achard *et al* 2004). The tropics were then stratified into 'hotspot' and 'non-hotspot' regions, and Landsat scenes were sampled more intensively in the hotspot areas. As with the FAO analysis, these scenes

were classified visually and included a number of different land cover types from which it may be possible to distinguish degradation in addition to deforestation. The stratification by hotspots means that greater accuracy in the areas of greatest change may be achieved. Achard *et al* (2002, 2004) estimate continental-scale carbon emissions from deforestation and forest degradation, but the sampling scheme was not designed for, nor sufficient for national-level assessments. Another recent study of the global humid tropics used MODIS data to identify areas of low, medium and high change rates, and then sampled within each of these areas (Hansen *et al* 2008a, 2008b). The value of this approach is that the coarser, MODIS-based stratification provides a basis for extrapolating the sample-based rates over the entire study area.

6.2. Wall-to-wall assessments with Landsat and AVHRR

A pan-tropical wall-to-wall global assessment of deforestation in the 1980s and 1990s was conducted using coarse resolution data (8 km AVHRR; DeFries *et al* 2002, Hansen and DeFries 2004). As the authors acknowledge, the precision of these data is not appropriate for determination of country-level deforestation. It provides only an indication of large-scale forest change.

There are numerous country-level wall-to-wall assessments of deforestation, most of which have used Landsat or Landsat-like data. At the national level, Brazil and India have conducted comprehensive, high-resolution estimates of forest change. Brazil estimates deforestation annually using this technique (INPE 2007). In other cases, international NGOs or academic institutions have conducted these assessments with local collaborators. Examples of countries that have completed wall-to-wall analyses are provided in table 3 below. A regional assessment of the Congo Basin has also been completed, providing a helpful example of potential country-level assessments using a combination of remote sensing data (MODIS and Landsat) (Hansen *et al* 2008a). The coarser resolution but more frequently acquired data allowed the study to have greater temporal resolution to help account for cloud cover and assess large-scale degradation. Additional regional efforts are currently underway in the tropical Andes and non-Brazilian Amazon including Bolivia, Colombia, Ecuador, Peru and Venezuela. At this time most of these wall-to-wall efforts only measure change in forest and non-forest, not degradation.

With additional data and analysis (and thus added time and cost) wall-to-wall analysis can be used to assess degradation by using imagery with greater temporal frequency and by classifying the imagery to a greater level of detail. These measurements will have higher uncertainty than those for deforestation, which will need to be quantified. A few regional, satellite-based studies of selective logging in the Brazilian Amazon have tested automated wall-to-wall detection of forest management and shown it is possible in regions without substantial topography (Souza *et al* 2005, Asner *et al* 2005, Oliveira *et al* 2007).

In summary, all of the sampling remote sensing efforts to date are pan-tropical assessments that provide estimates of deforestation on a regional basis, not by country. Wall-to-wall efforts have been completed for a number of countries demonstrating the viability of this method for measuring

Table 3. Comparison of annual deforested area as reported by FAO to that determined by various wall-to-wall assessments of remote sensing data. The FAO data used are from the Global Forest Resources Assessment for the year 2005 (FAO 2006).

	Annual deforestation rates									
	Brazil		Paraguay	Bolivia		Argentina		Liberia	Myanmar	Peru
Dates	1990–2000	2000–2005	1990–2000	1990–2000	2000–2005	1990–2000	2000–2005	1990–2000	1990–2000	2000–2005
FAO (ha/year)	–2681 000	–3103 000	–179 000	–270 000	–270 000	–149 000	–150 000	–60 000	–466 000	–94 000
Alt. Dates				1992–2001	2001–2004	1998–2002	2002–2006	1986–2000		1999–2005
Wall to Wall (ha/year)	–1700 300	–2214 868	–254 603	–150 600	–224 700	–195 483	–298 302	–22 857	–120 000	–64 700
Wall to wall area included	Amazon only		Entire country	Only Bolivian Amazon (Eastern lowland) Does not include Dry Chaco		Only Eastern Chaco forest in 6 provinces with highest deforestation rates		Entire country	Entire country	79% of Amazon
Wall to wall forest definition used ^a	Same as FAO		Deforestation is conversion of forest to non-forest	Deforestation is conversion of humid/semi-humid forest cover to non-forest. Analysis excludes secondary forest growth, plantations, and dry montane forests		Deforestation defined as loss of native forest. Analysis excludes degradation and secondary regeneration.		Deforestation is loss of forest. Forest is closed canopy cover greater than 80%. Anything less is non-forest	Deforestation is loss of forest. Forest is defined as closed-canopy cover greater than 50% and tree height greater than 5 m.	Same as FAO
Wall to wall method ^b	Landsat TM		Landsat TM	Landsat TM		Landsat TM		Landsat ETM+	ASTER	Landsat ETM+
Wall to wall source	http://www.obt.inpe.br/prodes/		Huang <i>et al</i> (2007)	Killeen <i>et al</i> (2007)		UMSEF, June 2007. http://www.ambiente.gov.ar/archivos/web/UMSEF/File/2006_monitoreo_bosque_nativo_preliminar.pdf		Christie <i>et al</i> (2007)	Leimgruber <i>et al</i> (2005)	Oliveira <i>et al</i> (2007)

^a FAO definition—Forest is defined as trees higher than 5 m stands spanning 0.5 sq ha with tree cover greater than 10%. Definition excludes tree stands in agricultural production systems, for example in fruit plantations and agroforestry systems.

^b FAO method—national surveys.

deforestation reference scenarios. More work will be required to include forest degradation in these assessments. Verification with high-resolution satellite or field data will be needed to determine the accuracy of these different wall-to-wall assessments.

At this time the only country-level data available comes from these wall-to-wall assessments and FAO national statistics data. Table 3 summarizes existing studies of country-level deforestation from wall-to-wall assessments that used moderate to high-resolution data as compared to FAO data for comparable years. As expected, there are significant differences between the two methods as well as among the different wall-to-wall methods. A similar comparison was done for the Congo Basin assessment that used a variety of different remote sensing products (Hansen *et al* 2006).

7. Estimating carbon emissions from deforestation and forest degradation reference scenarios

To estimate reference carbon emissions, we need to combine measurements of deforestation and degradation with estimates of biomass carbon stocks. Data sources and methods to estimate carbon stocks are described in detail elsewhere (IPCC 2003, 2006, Gibbs *et al* 2007, Brown 1997, 2002, GOF-GOLD 2007). In general, tropical forest carbon stocks cannot yet be reliably estimated across large areas from remote sensing instruments. Thus carbon stock estimates for broad forest strata or categories that can be linked to satellite-based deforestation and forest degradation analyses will likely be the most feasible approach to quantify carbon emissions for reference scenarios (Gibbs *et al* 2007).

Carbon stocks for these broad forest categories can be estimated using default values (e.g., biome averages from the literature) or preferably from ground-based measurements (e.g., tree height and diameter at breast height, destructive harvest) collected using a national-level sampling scheme stratified by forest type and condition (see Gibbs *et al* 2007 for further explanation).

Ideally the same satellite observations used to estimate changes in forest cover will be used to identify the broad forest categories stratified by type and condition (i.e. logged, degraded, intact) used to apply the biome averages or design the sampling scheme for collecting ground-based forest carbon measurements. If the carbon stock and forest change data are compatible, then the average carbon stock values for each forest strata can be applied to deforestation and forest degradation reference scenarios to quantify national-level forest emissions (Gibbs *et al* 2007).

8. Conclusions

As the discussion above demonstrates, there are a number of important technical issues and decisions to resolve before a REDD program can be put in place. However, we believe these issues are resolvable with the use of additional sources of data.

Assessments of historical trends in deforestation are limited to data that have been previously collected. Field inventory data on tropical deforestation are sparse and

inconsistent and the time required to acquire more data makes this approach infeasible for measuring reference forest change in the near term. Freely available Landsat images can provide reliable measurements of forest change, especially if complemented with coarser resolution satellite imagery, such as MODIS, to fill gaps caused by clouds and shadows, and to address questions of seasonality. All of the data sources included in table 1 can be used to fill gaps in the Landsat data, with the high-resolution data also valuable for validation, although each has some constraint such as limited coverage in space or time, resolution too coarse to detect small to moderate scale forest change, being technically challenging, or expensive. Radar imagery from ERS, Radarsat and JERS-1 would be particularly useful because it can see through clouds. Particularly if a more recent reference scenario using 2007 or 2008 can be used because data from the recent ALOS-PalSAR sensor will likely provide much improved wall-to-wall monitoring across the pan-tropics without hindrance from clouds. Tests are underway to see whether the combined optical and radar sensors on this satellite can be used for direct estimates of biomass (Kellndorfer *et al* 2007).

It may be helpful to establish standardized methods for the analysis of remote sensing data, and it will be necessary to establish transparency and verification requirements that include some assessment of uncertainty. More pervasive field inventories and surveys can be used to measure and validate remote sensing results providing key 'reality checks' to the overall system of land cover classification and change detection. These same surveys can be used to enhance existing data on forest carbon stocks, which is greatly needed to assess the emissions from deforestation (Gibbs *et al* 2007). Methods for assessing accuracy/error should be transparent and widely accepted.

Providing access to free or low-cost high-resolution imagery should be a priority for international support. Grant programs also need to help countries set up national remote sensing assessments and to train technicians.

Acknowledgments

We thank the Coalition for Rainforest Nations for supporting the initial review of methods and concepts for measuring historical reference periods for reference scenario for REDD, and for hosting a workshop that helped expand and improve this work. We would also like to thank John Niles for his guidance in the early stages of this work and Megan Dawson for her careful and committed work on this paper. We further thank three anonymous reviewers for constructive comments.

References

- Achard F, DeFries R, Eva H, Hansen M, Mayaux P and Stibig H-J 2007 Pan-tropical monitoring of deforestation *Environ. Res. Lett.* **2** 045022
- Achard F, Eva H D, Stibig H-J, Mayaux P, Gallego J, Richards T and Malingreau J-P 2002 Determination of deforestation rates of the world's humid tropical forests *Science* **297** 999–1002

- Achard F, Eva H D, Mayaux P, Stibig H-J and Belward A 2004 Improved estimates of net carbon emissions from land cover change in the tropics for the 1990s *Glob. Biogeochem. Cycles* **18** GB2008
- Agbu P A and James M E 1994 *The NOAA/NASA Pathfinder AVHRR Land Data Set Users' Manual* (Greenbelt, MD: Goddard Distribution Active Archive Center Publications, GCDG)
- Asner G P 2001 Cloud cover in Landsat observations of the Brazilian Amazon *Int. J. Remote Sens.* **22** 3855–62
- Asner G P, Knapp D E, Broadbent E N, Oliveira P J C, Keller M and Silva J N 2005 Selective logging in the Brazilian Amazon *Science* **310** 480–2
- Brown S 1997 Estimating biomass and biomass change of tropical forests: a primer *FAO Forestry Paper no. 134* (Rome: FAO)
- Brown S 2002 Measuring carbon in forests: current status and future challenges *Environ. Pollut.* **116** 363–72
- Christie T, Steininger M K, Juhn D and Peal A 2007 Fragmentation and clearance of Liberia's forests: 1986–2000 *Oryx* **41** 539–43
- Czaplewski R L 2003 Can a sample of Landsat sensor scenes reliably estimate the global extent of tropical deforestation? *Int. J. Remote Sens.* **24** 1409–12
- DeFries R, Achard F, Brown S, Herold M, Murdiyarto D, Schlamadinger B and de Souza C 2006 Reducing greenhouse gas emissions from deforestation in developing countries: considerations for monitoring and measuring *GOFC-GOLD/GTOS Report No. 26*
- DeFries R, Achard F, Brown S, Herold M, Murdiyarto D, Schlamadinger B and de Souza C Jr 2007 Earth observations for estimating greenhouse gas emissions from deforestation in developing countries *Environ. Sci. Policy* **10** 385–94
- DeFries R S, Asner G, Achard F, Justice C, Laporte N, Price K, Small C and Townshend J 2005 Monitoring tropical deforestation for emerging carbon markets *Reduction of Tropical Deforestation and Climate Change Mitigation* ed P Mountinho and S Schwartzman (Washington, DC: Instituto de Pesquisa Ambiental de Amazonia (IPAM))
- DeFries R S, Houghton R A, Hansen M C, Field C B, Skole D and Townshend J 2002 Carbon emissions from tropical deforestation and regrowth based on satellite observations for the 1980s and 1990s *Proc. Natl Acad. Sci. USA* **99** 14256–61
- EORC 2008 ALOS Science program. Earth Observation Research Center, Japanese Space Agency (JAXA) http://www.eorc.jaxa.jp/ALOS/sci/sci_index.htm
- FAO (Food and Agricultural Organization of the United Nations) 2001 Global forest resources assessment 2000 *FAO Forestry paper 140* 479 p
- FAO (Food and Agriculture Organization of the United Nations) 2006 Global forest resources assessment 2005-main report *FAO Forestry Paper No. 147* (Rome: FAO)
- Gibbs H K, Brown S, Foley J A and Niles J O 2007 monitoring and estimating tropical forest carbon stocks: making REDD and reality *Environ. Res. Lett.* **2** 045023
- GOFC-GOLD 2007 Reducing greenhouse gas emissions from deforestation and degradation in developing countries: a sourcebook of methods and procedures for monitoring, measuring and reporting. GOFC-GOLD Project Office, hosted by Natural Resources Canada, Alberta, Canada.
- Grainger A 1996 An evaluation of the FAO tropical resource assessment, 1990 *Geogr. J.* **162** 73–9
- GRFM 2008 Global Rain Forest Mapping project <http://southport.jpl.nasa.gov/GRFM/>
- Gullison R E *et al* 2007 Tropical forests and climate policy *Science* **316** 985–6
- Hansen M C and DeFries R S 2004 Detecting long term global forest change using continuous fields of tree cover maps from 8 km AVHRR data for the years 1982–1999 *Ecosystems* **7** 295–716
- Hansen M C, Devers D, Mayaux Ph, Dfourny P and Duveiller G 2006 *The Forests of the Congo Basin: State of the Forest 2006* chapter 9, Central African forest cover and cover change mapping pp 80–90 http://carpe.umd.edu/resources/Documents/THE_FORESTS_OF_THE_CONGO_BASIN_State_of_the_Forest_2006.pdf/view
- Hansen M C, Roy D P, Lindquist E, Adusei B, Justice C O and Altstatt A 2008a A method for integrating MODIS and landsat data for systematic monitoring of forest cover and change in the Congo Basin *Remote Sens. Environ.* **112** 2495–513
- Hansen M C *et al* 2008b Humid tropical forest clearing from 2000 to 2005 quantified using multi-temporal and multi-resolution remotely sensed data *Proc. Natl Acad. Sci.* at press
- Hayes D J and Cohen W B 2007 Spatial, spectral and temporal patterns of tropical forest cover change as observed with multiple scales of optical satellite data *Remote Sens. Environ.* **106** 1–17
- Hayes D J, Cohen W B, Sader S A and Irwin D E 2008 Estimating proportional change in forest cover as a continuous variable from multi-year MODIS data *Remote Sens. Environ.* **112** 735–49
- Huang C, Kim S, Altstatt A, Townshend J R G, Davis P, Song K, Tucker C J, Rodas O, Yanosky A, Clay R and Musinsky J 2007 Rapid loss of Paraguay's Atlantic forest and the status of protected areas—A Landsat assessment *Remote Sens. Environ.* **106** 460–6
- INPE 2007 Monitoramento da floresta Amazonica Brasileira por satellite <http://www.obt.inpe.br/prodes/>
- IPCC (Intergovernmental Panel on Climate Change) 2003 Good Practice Guidance for Land Use, Land-Use Change and Forestry, ed J Penman, M Gytarsky, T Hiraishi, T Krug, D Kruger, R Pipatti, L Buendia, K Miwa, T Ngara, K Tanabe and F Wagner (Hayama, Japan: IPCC/IGES) <http://www.ipccnggip.iges.or.jp/public/gpoglucf/gpoglucf.htm>
- IPCC (Intergovernmental Panel on Climate Change) 2006 2006 *IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme* ed HS Eggleston, L Buendia, K Miwa, T Ngara and K Tanabe (Japan: IGES) pp 437–40
- IPCC (Intergovernmental Panel on Climate Change) 2007 *Climate Change 2007: The Physical Science Basis: Summary for Policymakers* http://www.ipcc.ch/wg1_spm_17apr07.pdf
- Josse C *et al* 2007 Ecological Systems of the Amazon Basin of Peru and Bolivia *Clasificación and Mapping* (Arlington, VA: NatureServe)
- Kellndorfer J, Shimada M, Roseqvist A, Walker W, Kirsch K, Nepstad D, Laporte N, Stickler C and Lefebvre P 2007 *New Eyes in the Sky: Could-free Tropical Forest Monitoring for REDD with the Japanese Advanced Land Observing Satellite (ALOS)* (MA: The Woods Hole Research Center)
- Killeen T J, Calderon V, Soriana L, Quezada B, Steininger M K, Harper G, Solorzano L A and Tucker T J 2007 Thirty years of land-cover change in Bolivia: exponential growth and no end in sight *Ambio* **36** 600–6
- Leimgruber P, Kelly D S, Steininger M K, Brunner J, Muller T and Songer M 2005 Forest cover change patterns in Myanmar (Burma) 1990–2000 *Environ. Conserv.* **32** 356–64
- Matthews E 2001 *Understanding the FRA 2000* (Washington, DC: World Resources Institute)
- Mayaux P, Holmgren P, Achard F, Eva H, Stibig H-J and Branthomme A 2005 Tropical forest cover change in the 1990s and options for future monitoring *Phil. Trans. R. Soc. B* **360** 373–84
- MDA Federal 2004 *Landsat GeoCover ETM+ 2000 Edition Mosaics and 1990 Edition Mosaics, 1.0*, USGS, Sioux Falls, South Dakota, 2000
- Milne R and Jallow B P (Lead authors) 1996 Basis for consistent representation of land areas *IPCC Good Practice Guidance for LULUCF* chapter 2
- Navarro G and Ferreira W 2007 *Mapa de Vegetación de Bolivia Cochabamba, Bolivia* <http://conserveonline.org>
- Olander L P and Murray B C 2007 A new opportunity to help mitigate climate change, save forests, and reach development goals *Nicholas Institute Working Paper* <http://www.env.duke.edu/institute/products.html>

- Oliveira P J C, Asner G, Knapp D E, Almeyda A, Galvan-Gildemeister R, Keene S, Raybin R F and Smith R C 2007 Land-use allocation protects the Peruvian Amazon *Science* **317** 1233–6
- Ramankutty N, Gibbs H K, Achard F, DeFries R, Foley J A and Houghton R A 2007 Challenges to estimating carbon emissions from tropical deforestation *Glob. Change Biol.* **13** 51–66
- Rosenqvist A, Shimada M and Watanabe M 2007 ALOS PALSAR: A pathfinder mission for global-scale monitoring of the environment *IEEE Trans. Geosci. Remote Sens.* **45** 3307–16
- Roy P S, Ranganath B K, Diwakar P G, Vohra T P S, Bhan S K, Singh I J and Pandian V C 1991 Tropical forest type mapping and monitoring using remote sensing *Int. J. Remote Sens.* **12** 2205–25
- Sader S A, Waide R B, Lawrence W T and Joyce A T 1989 Tropical forest biomass and successional age class relationships to a vegetation index derived from Landsat TM data *Remote Sens. Environ.* **28** 143–56
- Souza C M, Roberts D A and Cochrane M A 2005 Combining spectral and spatial information to map canopy damage from selective logging and forest fires *Remote Sens. Environ.* **98** 329–43
- Steininger M K 1996 Tropical secondary forest regrowth in the Amazon: age, area and change estimation with Thematic Mapper data *Int. J. Remote Sens.* **17** 9–27
- Steininger M K, Tucker C, Townshend J R G, Killeen T J, Desch A, Bell V and Ersts P 2001 Tropical deforestation in the Bolivian Amazon *Environ. Conserv.* **28** 127–34
- Tucker C J, Grant D M and Dykstra J D 2004 NASA's global orthorectified Landsat data set *Photogramm. Eng. Remote Sens.* **70** 313–22
- Tucker J C and Townshend J R G 2000 Strategies for monitoring tropical deforestation using satellite data *Int. J. Remote Sens.* **21** 1461–72
- UMSEF 2002 *Mapping Native Forest Land in Argentina* http://www2.medioambiente.gov.ar/documentos/bosques/umsef/cartografia/deforestacion_argentina.pdf
- UNFCCC 2008 *Report of the Conf. Parties on its Thirteenth Session, held in Bali from 3 to 15 December 2007. Add Part Two: Action taken by the Conf. Parties at its Thirteenth Session* FCCC/CP/2007/6/Add.1
- UNFCCC 2007 Subsidiary Body for Scientific and Technological Advice—Country submissions, Twenty-sixth session. Bonn, 7–18 May 2007 <http://unfccc.int/meetings/sb24/items/3648.php>
- UNFCCC 2006 Background paper for the workshop on reducing emissions from deforestation in developing countries, August 2006, Rome, Italy. Part I. Scientific, socio-economic, technical and methodological issues related to deforestation in developing countries *Working paper No.1 (a)*
- USGS 2008 Imagery for Everyone: Timeline set to release entire USGS Landsat archive at no charge Technical Announcement April, 2008 <http://landsat.usgs.gov/> accessed 21 April 2008
- Zwick S 2007 Are forests like a bag of beans? Conversations on REDD in Bali *Ecosystem Marketplace News* 14 December 2007