ISSN 0258-6150

FAO FORESTRY PAPER

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Global forest land-use change 1990–2005



European Commission

Cover photos:
Left: Western hemlock, Tsuga heterophylla natural forest, Alaska (B. Ciesla)
Centre: RGB composition (Band 5, 4 and 3) from Landsat 7, over a 20km by 20 km tile located at 72° West and 38° South, Chile (U.S geological survey)
Right: Forest cleared for agriculture, Thailand (FAO/14639/K. Boldt)

Global forest land-use change 1990–2005

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FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS
Rome, 2012

Please cite as: **FAO & JRC.** 2012. *Global forest land-use change 1990–2005*, by E.J. Lindquist, R. D'Annunzio, A. Gerrand, K. MacDicken, F. Achard, R. Beuchle, A. Brink, H.D. Eva, P. Mayaux, J. San-Miguel-Ayanz & H-J. Stibig. FAO Forestry Paper No. 169. Food and Agriculture Organization of the United Nations and European Commission Joint Research Centre. Rome, FAO.

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ISBN 978-92-5-107399-5

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Acknowledgements

FAO and the European Commission Joint Research Centre (JRC) prepared this report on the Global Forest Resources Assessment (FRA) 2010 Remote Sensing Survey in partnership, and they express thanks for the assistance and input of many organizations, countries, donors, other partners and individual experts.

The major contribution to operational funding for the FRA 2010 Remote Sensing Survey for the period 2009–11 was made by the European Commission. Other support was provided through initial grants from the National Aeronautics and Space Administration, the Heinz Center, the Government of Australia and the Government of Finland.

The following governments are thanked for their contributions of extra-budgetary financial resources or secondments: those of Australia, Brazil, France, Norway and the United States of America.

More than 200 national-level forestry and remote sensing experts collaborated on this report, both directly and indirectly; they are listed in Annex 3. This collaboration was critical to the success of the FRA 2010 Remote Sensing Survey and is gratefully acknowledged.

The authors wish to thank the following FAO staff members for their contributions: Mette Løyche-Wilkie, Renato Cumani, Antonio Di Gregorio, Emma Foti, Monica Garzuglia, Stefano Giaccio, Örjan Jonsson, John Latham, Antonio Martucci, Marisalee Palermo, Anssi Pekkarinnen and Ilaria Rosati. Several FAO consultants were also involved: Ralph Ridder advised on sample design, Marieke Sandker reviewed thousands of remote sensing samples and assisted with database management, and Susan Iremonger updated maps of climatic domains.

The authors would also like to thank the following members of the JRC and its collaborator, the University of Louvain-La-Neuve, for their contributions: Catherine Bodart, Silvia Carboni, Pierre Defourny, François Donnay, Céline Ernst, Desirée Johansson, Pieter Kempeneers, Ouns Kissiyar, Andrea Lupi, Rastislav Raši, Roman Seliger, Dario Simonetti, Fernando Sedano, Lucia Seebach, Peter Strobl, Astrid Verheggen, Peter Vogt, Michael Vollmar and Carlos de Wasseige.

Tom Loveland and staff at the United States Geological Survey assisted in obtaining the large quantities of Landsat data required for the FRA 2010 Remote Sensing Survey. Matt Hansen, Peter Potapov and Anil Kommareddy (South Dakota State University) assisted with the preprocessing of the Landsat data used by FAO.

Foreword

The world's forests are critical for human livelihoods. Increasingly they are being recognized for the wide range of products and essential ecosystem services they provide. Accurate and up-to-date information on the extent of the world's forests, and the way they are changing, has never been more important.

The Food and Agriculture Organization of the United Nations (FAO) has been collecting data and reporting on the world's forests for more than 60 years. Its Global Forest Resources Assessment (FRA) collates, analyses and tabulates data supplied to FAO by countries on a wide range of forest-related variables and reports its results every five years. Of particular interest are change in forest area and the dynamics of forest losses (deforestation and, to a lesser extent, loss through natural causes) and gains (afforestation and natural expansion of forests, for example into abandoned agricultural land). Many countries, however, lack sufficient data or repeated, comparable measurements with which to make reliable assessments of forest change.

With the rapid development, in the last 40 years, of global, satellite-based monitoring, such as the long time-series of data generated by Landsat, better data than ever before are available with which to carry out a comprehensive global study on change in forest area. It is vital that we look at forest area – and the way it has changed in recent years – in more detail.

This report on the FRA 2010 Remote Sensing Survey is the first of its kind to present systematic estimates of global forest land use and change. It is the result of many years of planning and three years of detailed work by staff at FAO and the European Commission Joint Research Centre (JRC), with inputs from technical experts from more than 100 countries. From its outset, the ambitious goal of the FRA 2010 Remote Sensing Survey has been to use remote sensing data to obtain globally consistent estimates of forest area and changes in tree cover and forest land use between 1990 and 2005.

It has been said that "we can't manage what we can't measure". We are delighted at the partnership that has developed between FAO, the JRC and countries with the aim of ensuring that future decisions on forests are based on reliable information. This report is a firm step in that direction. We thank the authors and all contributors and recommend this report to all those who want to know how the world's forests are changing.

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Acronyms and abbreviations

ANOVA	analysis of variance
EOSD	Earth Observation for Sustainable Development of Forests (Canada)
FAO	Food and Agriculture Organization of the United Nations
FRA	Global Forest Resources Assessment (FAO)
GLS	Landsat Global Land Survey (United States Geological Survey)
ha	hectare(s)
IPCC	Intergovernmental Panel on Climate Change
JRC	European Commission Joint Research Centre
km	kilometre(s)
µm	micrometre(s)
MMU	minimum mapping unit
MODIS	Moderate Resolution Imaging Spectroradiometer
NFI	National Forest Inventory (Canada)
NLCD	National Land Cover Dataset (United States of America)
REML	restricted maximum likelihood
RSS	FRA Remote Sensing Survey
VCF	Vegetation Continuous Fields
WRS	Worldwide Reference System

Executive summary

This report presents the key findings on forest land use and land-use change between 1990 and 2005 from FAO's 2010 Global Forest Resources Assessment (FRA 2010) Remote Sensing Survey. This survey was the result of a partnership between FAO, countries and the European Commission Joint Research Centre (JRC). It is the first report of its kind to present systematic estimates of global forest land use and change.

A SYSTEMATIC SAMPLE FOR GLOBALLY CONSISTENT, STATISTICALLY RELIABLE RESULTS

The survey is based on a systematic sample of Landsat satellite imagery for the years 1990, 2000 and 2005 located at the intersection of each degree of longitude and latitude. Globally, 15 779 sample sites were processed for land cover and land use. The final number of sample sites analysed was 13 066 after accounting for sites with no data, statistical outliers and nation-specific review and revision (see Annex 1). The area surveyed at each sample site was 10 km × 10 km, providing a sampling intensity of about 1 percent of the global land surface.

FOREST LAND USE IS REPORTED

This report focuses on forest land use, not land cover. Forest land use is defined as areas with tree cover, or where management or natural processes will ultimately restore tree cover, and the predominant use is forestry. In some cases, forest land use may include land temporarily without tree cover, for example during cycles of shifting cultivation, forest plantations and even-age forest management. This approach is consistent with the forest definition used in FRA country reports and similar to the classes used in national reports under the United Nations Framework Convention on Climate Change.

FOREST AREA

The survey estimates the total area of the world's forests in 2005 at 3.8 billion hectares, or 30 percent of the global land area.

ANNUAL GLOBAL FOREST AREA LOSSES WERE GREATER IN 2000–2005 THAN IN 1990–2000

Overall, there was a net decrease in global forest area of 1.7 percent between 1990 and 2005, at an annual rate of change of 0.11 percent. This equates to an annual shift from forest land use to other land uses of 3 million hectares per year between 1990 and 2000 and of 6 million hectares per year between 2000 and 2005.

THERE WERE REGIONAL DIFFERENCES IN FOREST LOSS AND GAIN

Major regional differences were found in the net rates of forest area change; only Asia and North America experienced gains in forest area and all other regions saw net losses. South America had the highest net forest loss, losing some 3.3 million hectares annually between 1990 and 2005. Africa had the second highest net forest loss – 1.6 million hectares annually – during the same period. Europe, including the Russian Federation, had a net loss of 0.5 million hectares annually and Oceania lost just under 0.1 million hectares annually. North America experienced a net gain in forest area of 0.2 million hectares annually, while Asia had a net gain of 1.4 million hectares annually between 1990 and 2005.

FOREST LOSS WAS HIGHEST IN THE TROPICS

For this survey, forests were categorized according to four climatic domains: boreal, subtropical, temperate and tropical. There were significant gains in forest area in the boreal (0.9 million hectares annually) and subtropical (1.1 million hectares annually) between 1990 and 2005. There was also a net gain in forest area in the temperate domain of 0.9 million hectares annually over the same period.

In contrast, the tropical domain had a net loss of forest area of 6.8 million hectares annually between 1990 and 2005. This net reduction in forest land use was nearly 2.5 times the net forest area gained in the other three domains combined.

1. Introduction

Forests cover about 30 percent of the Earth's land area. At all spatial scales, from local to global, trees and forests play a critical role in human livelihoods, as well as in ecosystem functioning and health. In many local communities worldwide, people have a daily dependence on forests, engaging in fuelwood-gathering, the harvesting of wood and non-wood forest products, and community-based forest management. Forests also provide wood for larger-scale commercial purposes, habitat for more than half the world's terrestrial species, clean water, and other important ecosystem services.

Understanding the condition and changes through time of the globally valuable forest resource is important for human well-being and ecosystem health. For example, land-cover and land-use change can potentially affect regional and global climates by emitting or sequestering carbon (Pan *et al.*, 2011) and by altering the overall reflectance properties of the Earth's surface (Feddema *et al.*, 2005; Avissar and Werth, 2005).

FAO analyses and compiles data on the extent and state of the world's forests through a process called the Global Forest Resources Assessment (FRA). Published every 5–10 years, the FRA report reflects the major issues of concern prevalent at the time of reporting. In response to post-Second World War needs, early FRAs focused on timber stocks, while more recent editions, including FRA 2010 (FAO, 2010), have addressed topics such as forest biodiversity, forest carbon stocks and the social benefits of forests.

The FRA is an important information source for global efforts to sustainably manage forests, reduce the concentration of atmospheric greenhouse gases and advance other international initiatives. According to guidelines for national greenhouse gas inventories published by the Intergovernmental Panel on Climate Change (IPCC) (Paustian, Ravindranath and van Amstel, 2006), FAO is the main source of activity data and emission factors for forest and other land-use categories in Tier 1 calculations. The IPCC guidelines suggest that, where more detailed country data are unavailable, aggregate information can be obtained from international data sources such as the FRA.

THE FRA 2010 REMOTE SENSING SURVEY

The FRA 2010 Remote Sensing Survey was the result of a partnership between FAO, countries and the European Commission Joint Research Centre (JRC). Its goal was to obtain globally consistent information on the areal extent and changes in tree cover and forest land use between 1990 and 2005 at the regional, climatic domain and global levels. This report presents the results of the global forest land-use component of the survey.

2. Methods and materials

LAND COVER AND LAND USE

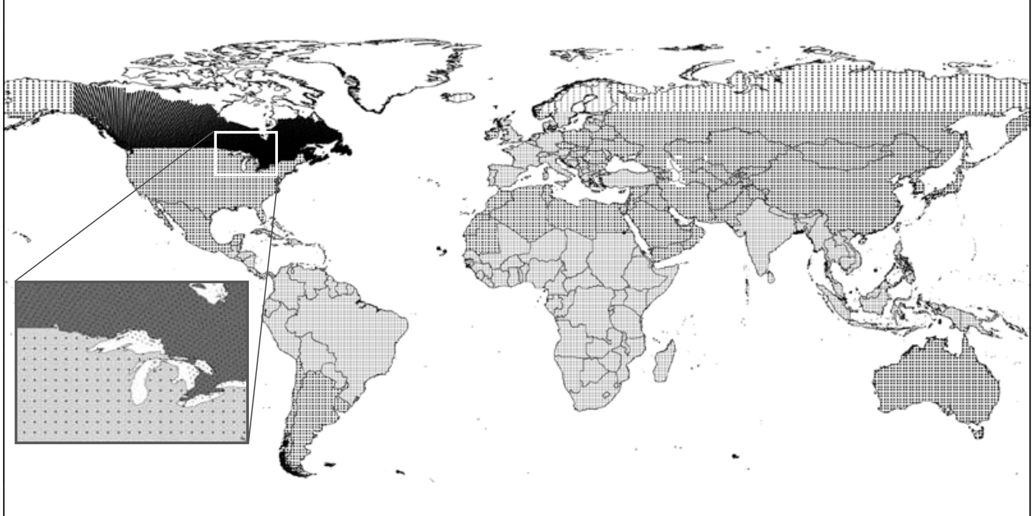
This report includes global statistics on forest land use derived from a land-cover classification and expert image interpretation. Land cover refers to the biophysical attributes of the Earth's surface and can be detected directly from aerial imagery or satellite-borne sensors. Land use implies a human dimension or purpose for which the land is used (Lambin *et al*., 2001). Land use can be inferred from remotely sensed data but typically must be verified by local expert knowledge or data collected in the field. Accurate information on land use is critical for understanding the causes of forest-cover change and for developing effective policies and strategies to slow and reverse forest loss.

SYSTEMATIC SAMPLE DESIGN

The survey used a systematic sample of 10 km x 10 km satellite image extracts at each 1-degree intersection of latitude and longitude (Mayaux *et al.*, 2005; Ridder, 2007). Globally, this is equivalent to a 1 percent sample of the Earth's land surface. Sampling intensity was reduced above 60 degrees latitude, north and south, to include only even degrees of longitude. This was done to avoid an increasing "weight" of samples in the high latitudes due to the curvature of the Earth. No sites were located higher than 75 degrees latitude, north or south. For Canada, the 1-degree grid was modified to use the Canadian National Forest Inventory's 20-km grid of smaller 4-km^2 photo points (Gillis, Omule and Brierley, 2005). The final sample grid consisted of 15 779 samples worldwide (Figure 1).

In a number of national, regional and global studies (e.g. Hansen *et al*., 2008; Stehman, Sohl and Loveland, 2005; Potapov *et al*., 2008; Eva *et al*., 2010), sampling approaches have proved successful in producing results for forest area change with acceptable and known precision. In previous remote sensing surveys, an approach

FIGURE 1
The 15 779 1-degree grid sample site locations used in the survey, with reduced intensity above 60° latitude north and south



Note: Canada samples were spaced on a 20-km grid to match the Canadian National Forest Inventory (inset; see Annex 1 and Annex 2). Sites processed by the JRC are in grey and sites processed by FAO are in black.

using a large sample of satellite imagery over broad geographic regions has been shown to suitably capture parameter estimates at the regional (i.e. > 100 000 hectares (ha)) and continental scales (Czaplewski, 2002).

A systematic sample was chosen for four main reasons (Ridder, 2007): land cover exhibits trends at the regional and continental scales and no *a priori* assumptions of forest area change intensity were considered; the layout of the latitude–longitude grid is not politically biased and is easy to understand; sample locations can easily be identified on maps; and FAO-supported national forest assessments are typically constructed based on the same grid.

IMAGERY DATA SOURCES

Imagery from the United States Geological Survey's Landsat Global Land Survey (GLS) provided the majority of data for classification and interpretation (Gutman *et al*., 2008). The Landsat sensor provides global coverage, a long time-series of acquisitions, and spatial and spectral characteristics suitable for the detection of changes in tree cover. Landsat acquisitions are referenced to the Earth's surface by a grid of paths and rows, called the Worldwide Reference System (WRS). The GLS is a spatially consistent, multi-epoch dataset composed of the best Landsat images for each WRS path/row covering most of the Earth's land surface and centred on the years 1975, 1990, 2000 and 2005.

For each sample site, Landsat optical bands 1–5 and 7 from the GLS1990, GLS2000 and GLS2005 datasets were compiled. These were clipped to a 20 km × 20 km box centred on each 1-degree latitude and longitude intersection to create imagery subsets. The central 10 km × 10 km of each image subset was used for area calculations and statistical analysis. In areas where the GLS acquisitions were cloudy or not seasonally matched, effort was made to obtain additional scenes from the Landsat data archive or directly from regional ground stations (for more detail see Beuchle *et al*., 2011; Potapov *et al.*, 2010; Seebach *et al.*, 2010).

For boreal, temperate and subtropical climatic domains, the GLS data were assumed to be the best available. If more than one GLS acquisition was available for a given site and date, the GLS acquisition with the lowest cloud cover was selected for classification (Lindquist *et al.*, submitted).

IMAGE PREPROCESSING

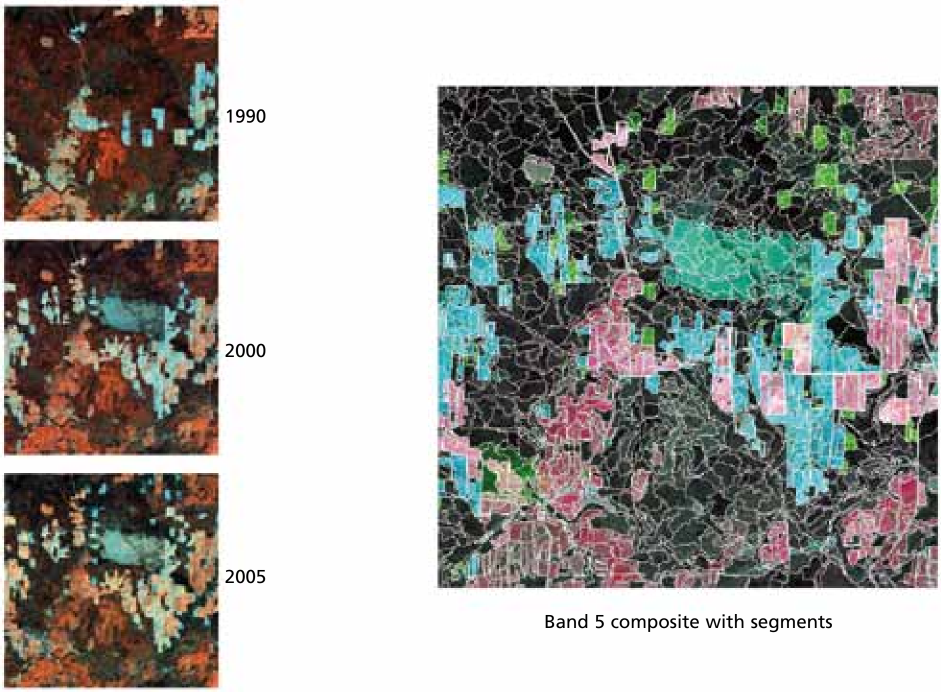
Images were preprocessed to correct for radiometric differences caused by changes in atmospheric quality or sensor characteristics between scene acquisition dates for the same site. Image normalization has the effect of standardizing digital number values relative to dense tree cover on a per-site basis and enables the more efficient application of automated classification algorithms (Toivonen *et al.*, 2006; Potapov *et al.*, 2010; Hansen *et al*., 2008). Potapov *et al.* (2010) describe the preprocessing methods used by the FAO team for areas outside the tropics. Bodart *et al*. (2011) describe the preprocessing methods used by the JRC team for the tropical and sub-Saharan Africa sites.

AUTOMATED LAND-COVER CLASSIFICATION

FAO and JRC both carried out automated land-cover classifications of preprocessed imagery. The JRC team processed sites within the tropics, sub-Saharan Africa (Beuchle *et al.*, 2011) and western Europe (Seebach *et al.*, 2010) as part of its ongoing TREES-3, MONDE and FOREST projects (JRC 2010; see Raši *et al.*, 2011 for details of the JRC land-cover classification processing chain). The FAO team processed all other sites (Figure 1). Although there were differences in the processing methods used by the two teams, the overall processing and importantly the output classifications are comparable. The processing methods consisted of the following common components:

- data acquisition;
- data preprocessing and image normalization;

FIGURE 2
Example of three imagery dates combined to make a single composite image with segments that capture reflectance changes in each period



Band 5 composite with segments

- image segmentation;
- image classification.

The automated segmentation of land-cover polygons and preclassification of land-cover types had two main goals: to create a spatially and temporally consistent dataset; and to avoid manual delineation, thus reducing the effort involved in the visual review and revision of land-cover and land-use labels.

The FAO–JRC land-cover classification methodology consisted of four main steps:

- image segmentation at level 1 (no minimum mapping unit – MMU) and level 2 (MMU approximately 5 ha in size);
- training data collection of representative sites for supervised classification;
- model construction and land-cover classification of level-1 objects;
- assignment of land-cover classification of level-2 objects.

All functions of segmentation and supervised classification were carried out using eCognition® image segmentation and processing software.[1]

Image segmentation is the process of partitioning an image by grouping similar pixels into patches called objects (regularly referred to as segments or polygons) based on spectral similarity and spatial distinctiveness. The criteria for creating image objects from individual pixels in eCognition can be controlled by the operator by specifying values for a series of parameters such as size, shape and the degree of similarity to be achieved in the segmentation. These values affect clustering and control the overall shape and size of the objects created (Baatz and Schappe, 2000).

A multi-date segmentation routine used Landsat image bands from all three survey periods to create a single layer containing objects based on the spectral information in each period (Figure 2). Image segmentation was implemented in two parts. The FAO

[1] www.ecognition.com/products/ecognition-developer.

method was similar to the segmentation routines described by Raši *et al.* (2011), using parameters that allowed the creation of small, irregular-shaped objects based on the spectral reflectance values of Landsat bands 3, 4 and 5 (0.63–1.75 µm). These bands were chosen for their ability to discriminate differences in surface reflectance caused by changes in vegetation type (Desclée, Bogaert and Defourny, 2006; Duveiller *et al.*, 2008). The first (i.e. level-1) segmentation created very small objects that ranged in size from a single Landsat pixel to greater than 100 ha and varied inversely with the spectral heterogeneity of the underlying Landsat image.

The most recent image (i.e. 2005) was segmented first. The objects created during this process were used to constrain the segmentation of the image for 2000 and, in turn, those objects constrained the segmentation of the 1990 image. For the tropics, the segmentation was first applied to the pair of 1990 and 2000 images, then the dissolved objects for 2000 were used to constrain the segmentation of the image for 2005.

The target MMU of the level-2 segments was 5 ha (Ridder, 2007). The desired MMU was achieved by aggregating level-1 segments smaller than 5 ha with adjacent objects with the most similar average Landsat band 5 reflectance. Short-wave infrared reflectance was used due to its effectiveness in forest mapping applications (Horler and Ahern, 1986; Hoffhine and Sader, 2002). Land-cover classification was carried out on the spectrally homogenous level-1 segments. The level-2 segments were assigned class labels according to the underlying percent composition defined by the level-1 segments (Table 1).

Given the large number of samples and the complexity involved in classifying each site, a supervised automated classification approach was selected as the best processing option. The overall classification methodology (depicted as a generalized flowchart in Figure 3) was as follows:

- For each site and date, a land-cover classification was produced with the following main classes – *tree cover*, *shrub cover*, *other land* (comprising herbaceous cover and bare ground/non-vegetated, which were grouped and not shown separately), *water* and *no data*. These classes were broadly in line with the IPCC land-use good-practice guidelines (Paustian, Ravindranath and van Amstel, 2006) when ultimately converted to land-use labels.
- Imagery from 2000 was classified first. When there was a low likelihood of detecting change between surveys, the class label for objects in the image object layer for 2000 was transferred to the 1990 and 2005 image object layers.
- The objects determined to have a relatively high likelihood of change between 1990 and 2000 and between 2000 and 2005 were classified separately using training data automatically selected from non-changing objects in the same period.
- The 5-ha MMU objects were assigned class labels according to the proportion of labelled level-1 objects they contained.

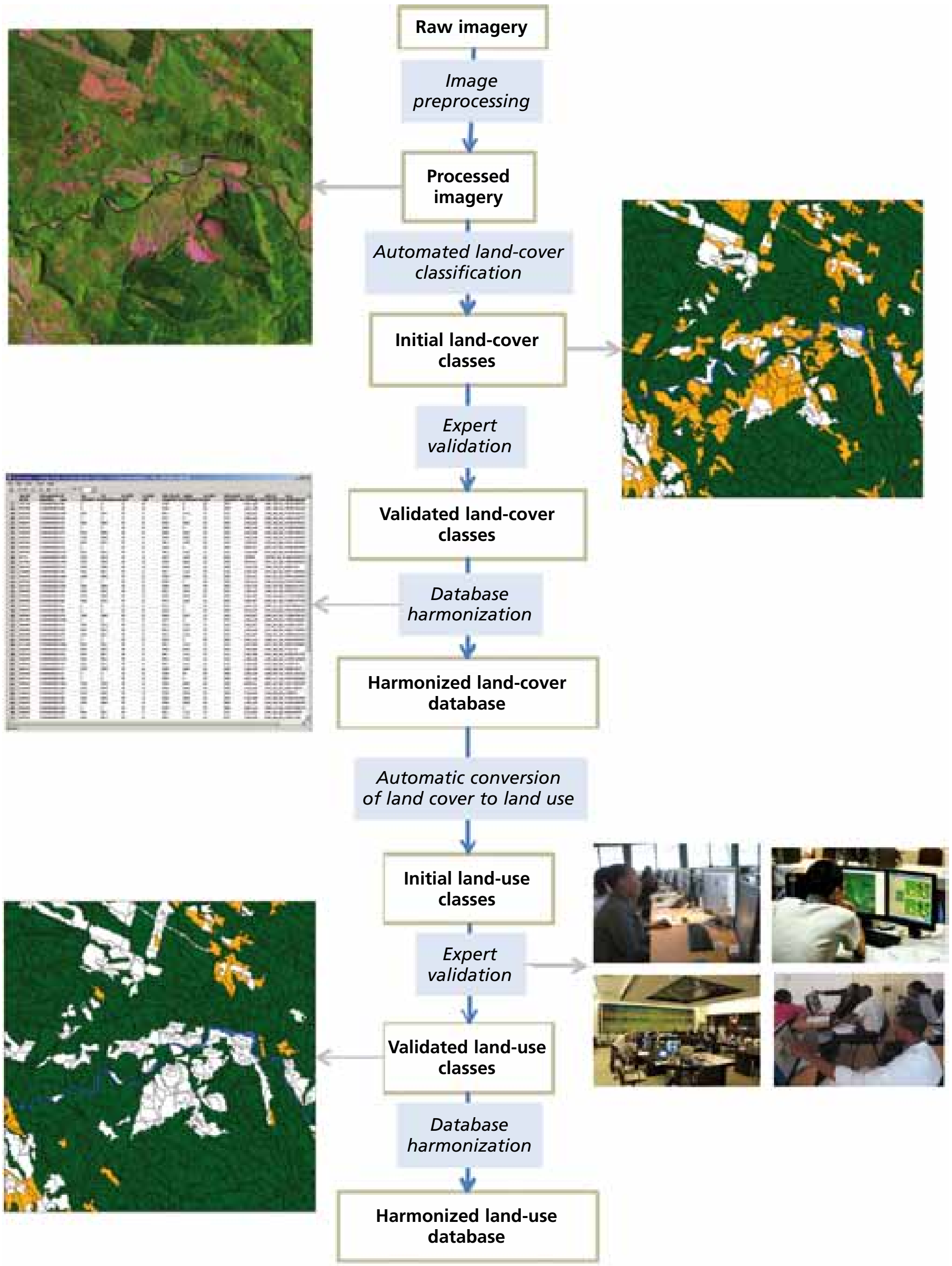
TRAINING THE CLASSIFICATION

The broad range of biophysical traits exhibited globally by tree cover presented a challenge for training data collection. For example, dense, dark, evergreen conifers have different characteristics to broad-leaved evergreens, which differ, in turn, from

TABLE 1
Level-2, 5-ha MMU land-cover labelling scheme based on the percent composition of underlying level-1 segments, listed in descending order of priority

Level-1 segment	% composition	Level-2 land-cover label
Tree cover	≥ 30	Tree cover
Other wooded land	≥ 70	Other wooded land
Other land cover	≥ 70	Other land cover
Water	≥ 70	Water

FIGURE 3
Generalized flowchart of the FAO processing chain



the characteristics of broad-leaved deciduous trees. The variations in biophysical features, changing seasonality and illumination conditions due to sun angle and slope position combine to affect the spectral reflectance properties of tree cover and make it difficult to create reflectance-based models that can accurately classify tree cover in its myriad forms globally. The FAO classification methodology attempted to account for this variation by applying a single method for creating tree-cover classification models globally to each sample site and period. At each sample site, therefore, three separate models of land-cover classification were created and applied, one for each period.

For sites in the boreal, temperate and subtropical domains, training labels for each land-cover class were assigned to level-1 image objects using temporally coincident year 2000 Moderate Resolution Imaging Spectroradiometer (MODIS) Vegetation Continuous Fields (VCF) (Hansen *et al*., 2003) and 2005 GlobCover (Arino *et al.,* 2008) land-cover products. Training class labels for water bodies were assigned based on the proportion of MODIS global water mask pixels (Carroll *et al.*, 2009) falling within an individual image object. Data from GlobCover were used to assist with the classification of shrub-dominated land cover.

Artificial neural network classifiers were used to produce land-cover classifications for the FAO-processed sample sites. For each site, the network was trained and then applied to all year 2000 image objects. Objects with the same or similar spectral characteristics in 1990 and 2005 as in 2000 were automatically assigned the land-cover label from the 2000 image object. Where a large spectral change was detected between 1990 and 2000 or between 2000 and 2005, the 1990 and 2005 image objects were assigned labels based on individually created 1990 and 2005 classification models. The methods are detailed in Lindquist *et al.* (submitted).

For the tropics, the object-based land-cover classification at level 1 was based on a supervised spectral library (Raši *et al.*, 2011). Spectral signatures were collected from a common set of training areas representing the main land-cover classes within the tropics. For this purpose, the preprocessed Landsat ETM+ data for the year 2000 of all sample sites in a subregion were used. For each main land-cover class, several subclasses were identified, representing spectral variations due to site condition or land-cover subtype. For *tree cover*, for example, identified subclasses were dense evergreen forests, degraded evergreen forests, dry deciduous forests, mangroves and swamp forest. For each subclass, several training areas were selected. The number of pixels ultimately used for establishing the spectral signature of a subclass was generally higher than 1 000. Spectral signature statistics (means and standard deviations) were calculated at the level of subclasses. For South and Southeast Asia, for example, 73 spectral signatures were established as inputs to the digital classification of the four main land-cover categories. A generic supervised classification of the level-1 segmentation objects was performed uniformly for all sample sites, based on membership functions established from the spectral signature of each subclass for the Landsat spectral bands 3, 4 and 5. The membership functions were defined as an approximation of the class probability distribution. These membership functions were then applied to the imagery of the three years, i.e. extending the spectral signatures to 1990 and 2005. The subclasses resulting from supervised classification were not mapped as separate thematic land-cover categories but contributed to the mapping of the four main land-cover classes.

The supervised classification result obtained for the level-1 objects served as direct input to the thematic aggregation done at the level-2 segmentation (with a 5-ha MMU). The labelling of the level-2 objects was performed by passing them though a sequential list of classification criteria (Table 1). For the purpose of forest monitoring, the main emphasis was on tree cover and tree-cover proportions within level-2 objects. For tropical sites, a *tree cover mosaic* class was introduced for objects containing partial tree cover at level 2: for example, a mapping unit containing 40 percent tree cover (= total area of aggregated tree-cover objects at level 1) was still labelled *tree cover mosaic*. Level-2 objects were the only image object labels considered for the expert review-and-revision process described in later sections.

LAND-USE CLASSES

Land-use classifications were based on FAO forest definitions (FAO, 2010), as follows:

- *Forest* – land spanning more than 0.5 ha with trees higher than 5 metres and canopy cover of more than 10 percent, or trees able to reach these thresholds *in situ*. It does not include land that is predominantly under agricultural or urban land use.
- *Other wooded land* – land not classified as *forest*, spanning more than 0.5 ha; with trees higher than 5 metres and canopy cover of 5–10 percent, or trees able to reach

these thresholds *in situ*, or with a combined cover of shrubs, bushes and trees above 10 percent. It does not include land that is predominantly under agricultural or urban land use.
- *Other land* – all land that is not classified as forest or other wooded land.

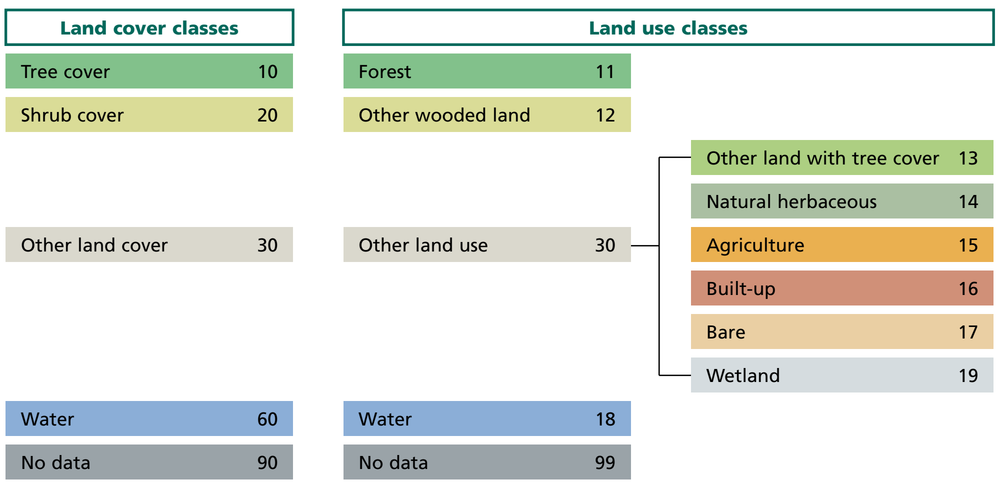
CONVERSION OF LAND COVER TO LAND USE

The conversion of land-cover class to land-use class was a two-step process. The first involved the automated conversion of land-cover classes to preliminary land-use labels (Figure 4). This conversion was presumed to account for the majority of polygons in the dataset. However, the accurate quantification of true land-use changes is complicated. The true land use of a given area must be examined in an ecological context that includes determining not only the vegetation present at the time of satellite image acquisition but also how the land will respond in the future (e.g. through regeneration, afforestation or deforestation) (Kurz, 2010).

Operationally, FAO definitions required expert human interpretation to provide the context necessary for the accurate categorization of land use, especially where exceptions to the automated rules existed. The exceptions were as follows (see also Figure 4):

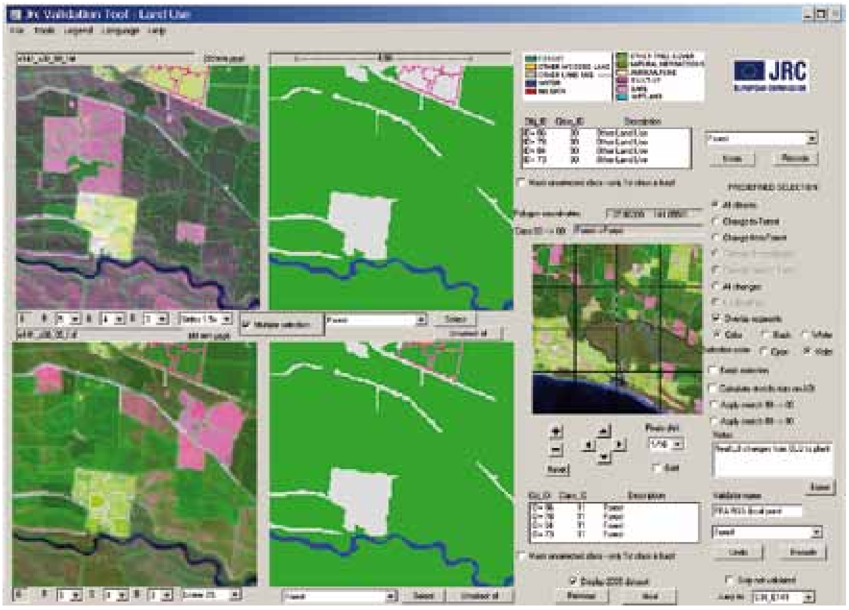
- The *tree cover* and *tree-cover mosaic* land-cover classes were converted to the *forest* land-use class. Experts looked for exceptions where the land uses were either urban (e.g. trees in parks or gardens around houses) or agricultural (e.g. orchards). Urban areas with trees, orchards, oil-palm plantations, agricultural land with trees, and areas under agroforestry were identified and manually re-coded as *other land use with tree cover.*
- *Shrub cover* was converted to the *other wooded land* land-use class. Experts looked for exceptions, such as forest re-growth where trees were likely to grow taller than 5 metres, and re-coded those areas as *forest.*
- *Other land cover* was converted to *other land use*. Experts looked for exceptions such as temporarily un-stocked areas that may have had no trees at the time of the image but were likely to regenerate or be replanted, in which case they were re-coded as *forest.*

FIGURE 4
Land-cover and land-use classes and their associated numeric codes



Note: In the conversion from land cover to land use, tree cover was converted to forest, shrub cover was converted to other wooded land, other land cover was converted to other land and water stayed as water. Ideally, where there was a change in land use either to or from forest, the subclasses of other land use were to be used to identify the cause of the change.

FIGURE 5
JRC validation tool user interface showing Landsat imagery from each survey period (left) and FAO land-use classes (centre)



EXPERT INTERPRETATION, VALIDATION AND CORRECTION OF LAND COVER AND LAND USE

The final assignment of land-cover and land-use labels was carried out by selected national forestry or remote sensing experts. The visual checks were conducted on all the imagery of three survey periods to review and revise the automatically assigned land-cover and land-use labels. The JRC developed a dedicated stand-alone computer application for this purpose (Simonetti, Beuchle and Eva, 2011). The aim of this tool was to provide a user-friendly interface, with an easy-to-use set of functions for navigating and assessing a given dataset of satellite imagery and land-cover/land-use maps, and to efficiently re-code areas where, according to expert judgement, changes were required (Figure 5).

Visual control and refinement of the digital classification results at object level 2 were implemented in three steps:

- Obvious errors from the automatic classification were corrected.
- At regional workshops, a revision of the mapping results was carried out by national experts, who contributed local forest knowledge to improve the interpretation. Nineteen regional workshops were held between September 2009 and July 2011, involving 204 national experts from 107 countries (Annex 3).
- In a final phase of regional harmonization, experienced image interpreters performed a final screening for errors overlooked or mistakenly re-introduced and controlled for interpretation consistency across the region, applying final corrections where necessary.

The review and revision of the classification was aided by very-high-resolution satellite imagery, Google Earth™, images from the Degree Confluence Project[2], Panoramio™, and existing vegetation maps, where available. Specific expert field knowledge was also important. The phase of visual control and refinement was designed as a crucial component for correcting classification errors and for implementing the change assessment.

[2] www.confluence.org.

3. Data analysis

All calculations used in this report are shown in Annex 4.

NO DATA

Areas obscured by cloud or otherwise lacking data due to poor satellite coverage or low-quality images were coded as “no data” in both the land-cover and land-use polygons. Cloud-affected and shadow-affected imagery was most common in the tropics (Ju and Roy, 2008; Asner, 2001); about 9 percent of the 4 016 tropical sample sites had no data for 2005. Where possible, areas obscured by cloud or shadow were re-coded manually based on an examination of the same location using images recorded at later or earlier dates, or by using national datasets, Google Earth® or local knowledge.

“No data” areas were considered an unbiased loss of information. If not resolved using the methods above, a “no data” classification encountered in one time period was passed to the land-cover and land-use label in all other time periods during analysis to ensure that only areas with viable data concurrent to all survey periods were analysed. Survey sites missing a Landsat acquisition for any of the time periods were removed from the analysis. Ultimately, 13 066 sites were processed to generate the results after all “no data” sites had been accounted for (Figure 6 and Annex 2).

The proportion of forest and gross gains and losses were calculated relative to the total area of all viable image objects, or “good land”. Good land was considered to be any object not classified as water or “no data” (Annex 4, equation 1).

ADJUSTMENT FOR LATITUDE AND AREA WEIGHTING

Due to the curvature of the Earth, the actual area represented by a latitude/longitude grid sample decreases with latitude. Analyses of forest area and forest-area change must take this into account by applying a correction to area measurements (Annex 4, equation 2).

Sites were also given a weight equivalent to the proportion of the total surveyed area represented by the site. Both latitude and area weights were incorporated in the survey analysis (Annex 4, equation 3).

FIGURE 6
Final 13 066 sites used in RSS 2010 analysis

Note: The large gap in the eastern part of the Russian Federation is due to a lack of Landsat imagery availability for 1990.

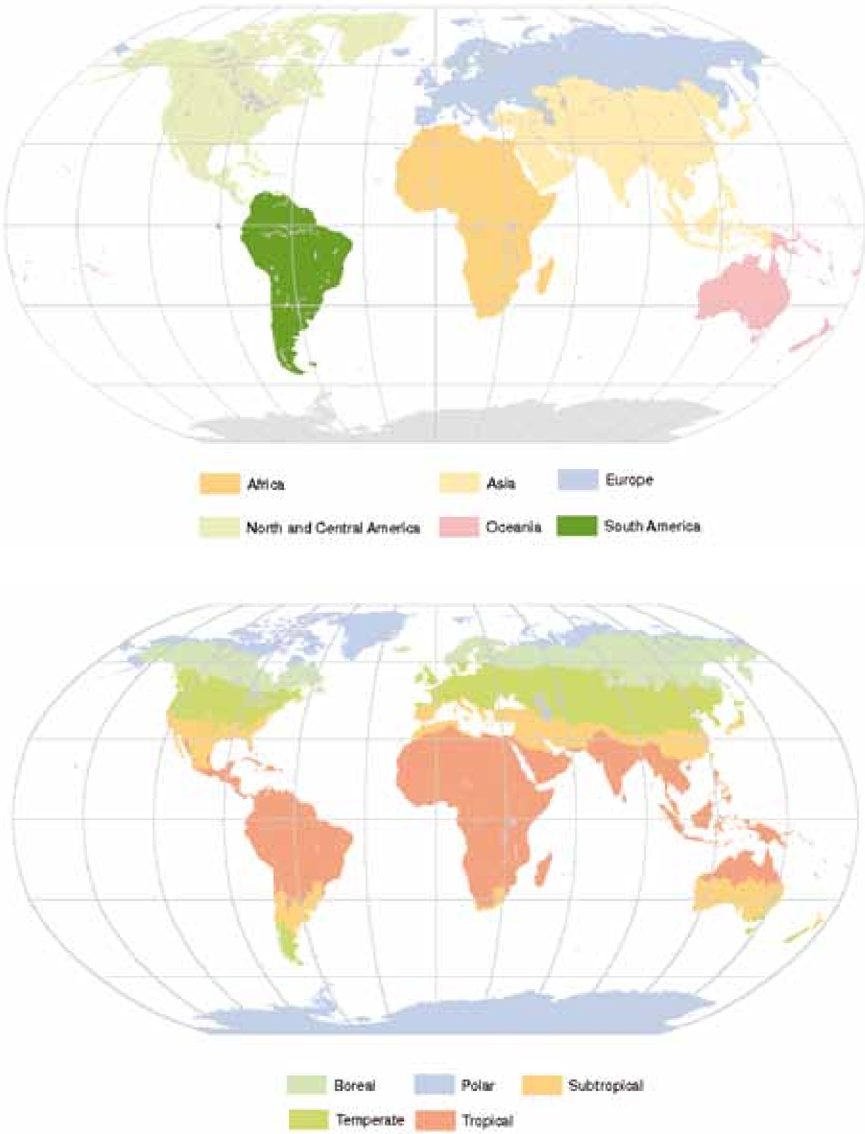
AGGREGATION FOR REGIONAL AND CLIMATIC DOMAIN ANALYSIS

Land-use classifications were summarized on a per plot basis and aggregated by FRA region and FAO climatic domain (Figure 7) (FAO 2012). Each survey site was assigned to the FRA region and FAO climatic domain within which the majority of the site was located. Survey data were analysed using the statistical software packages R (2.12.2) and Systat (Ver. 13).

FOREST AREA: GAINS AND LOSSES

Total forest area was determined using the Horvitz-Thompson direct estimator following Eva *et al.* (2010) – that is, by calculating the mean proportion of forest (Annex 4, equation 4) over all sample sites within a region or climatic domain and multiplying this figure by the total land area of the region. Forest area for each site was calculated at the nominal date of image acquisition, i.e. without taking the real acquisition date into account. Global forest area totals were calculated by summing the total forest area per region. This was done because confidence intervals for regional totals were smaller than for climatic

FIGURE 7
Regions (a) and climatic domains (b) used for aggregation and analysis



domains (Table 2). A similar approach was used to calculate gross and net forest area gains and losses. All calculations were made using the Mollweide equal area map projection.

ANNUALIZING FOREST-AREA CHANGE

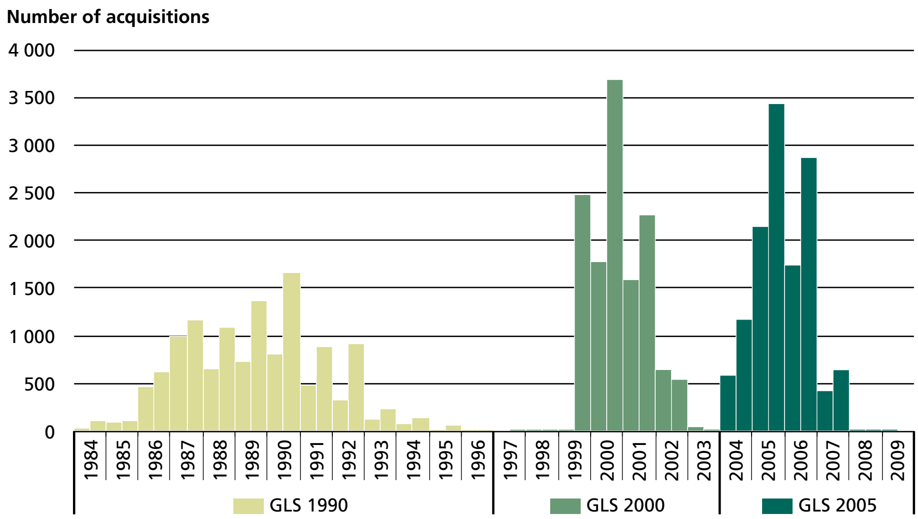
The satellite imagery used in the survey, while nominally representing 1990, 2000 and 2005, was acquired over a range of dates around the target year (Figure 8). Changes were calculated as mean annual changes, based on the date range represented by the imagery acquisition date at each site (Annex 4, equation 5).

TABLE 2
Mean forest area ('000 ha ± confidence interval) by region and climatic domain, 1990, 2000 and 2005

		Forest area ('000 ha)					
Region	**n**	**1990**		**2000**		**2005**	
Africa	2 322	520 000	± 7%	510 000	± 7%	490 000	± 8%
Asia	2 863	500 000	± 7%	510 000	± 7%	510 000	± 7%
Europe	907	1 080 000	± 5%	1 070 000	± 5%	1 070 000	± 5%
North and Central America	4 833	790 000	± 3%	800 000	± 3%	800 000	± 3%
Oceania	769	120 000	± 14%	120 000	± 14%	120 000	± 14%
South America	1 372	860 000	± 5%	820 000	± 5%	800 000	± 5%
World	13 066	3 860 000	± 2%	3 820 000	± 2%	3 790 000	± 2%
Climatic domain	**n**	**1990**		**2000**		**2005**	
Boreal	3 092	1 180 000	± 3%	1 190 000	± 3%	1 200 000	± 3%
Subtropical	1 958	320 000	± 8%	330 000	± 8%	330 000	± 8%
Temperate	3 831	560 000	± 5%	570 000	± 5%	570 000	± 5%
Tropical	4 185	1 730 000	± 4%	1 670 000	± 4%	1 620 000	± 4%

Note: n = number of sample sites. The sum of the forest areas of all regions was used as the global forest area total.

FIGURE 8
Range of dates of satellite imagery used for each survey period



	GLS 1990	GLS 2000	GLS 2005
Min	17/04/84	22/06/96	14/08/03
Max	22/08/96	22/05/03	11/05/09
Average	15/08/89	06/11/00	28/11/05
Median	07/08/89	12/09/00	01/10/05

Note: The table lists the earliest, latest, average and median dates for each survey period.

ERROR

The statistical precision of all estimates are reported as the values from the 95 percent confidence interval expressed as percent of the mean (Annex 4, equations 6–8). Reported errors are sampling errors only and do not account for classification errors or other sources of error.

4. Results and discussion

The statistical significance of weighted, annualized gains and losses in gross forest area and net change in forest area was tested for regions and climatic domains using several analyses:

- Welsh's t-test (two-tailed) to indicate whether the gains, losses and net change are different from 0 (Table 3);
- general linear models to calculate slopes and the significance of intercept and slope (Table 4);

TABLE 3
Significance of net annual changes and gross annual gains and losses for regions and climatic domains

	Significant change, 1990–2000			Significant change, 2000–2005		
	net	gain	loss	net	gain	loss
Domain						
Boreal	*	*	*	*	*	*
Subtropical	*	*	*	*	*	*
Temperate	*	*	*	*	*	*
Tropical	*	*	*	*	*	*
Region						
Africa	*	*	*	*	*	*
Asia	*	*	*	*	*	*
Europe		*	*		*	*
North and Central America	*	*	*		*	*
Oceania	*	*	*		*	*
South America	*	*	*	*	*	*
World	*	*	*	*	*	*

Note: * indicates a value significantly different from 0 ($p < 0.05$) using Welsh's t-test.

TABLE 4
***P* values for the slope of the line formed by a general linear model relating annualized net change and gross gains and losses with survey period by regions and climatic domains**

	Net		Gain	Loss
Domain				
Boreal	0.167		0.000	0.001
Subtropical	0.895		0.178	0.009
Temperate	0.018	↑	0.003	0.417
Tropical	0.000	↓	0.664	0.000
Region				
Africa	0.000	↓	0.787	0.000
Asia	0.515		0.014	0.122
Europe	0.133		0.646	0.030
North and Central America	0.027	↑	0.000	0.339
Oceania	0.595		0.438	0.780
South America	0.001	↓	0.928	0.000
World	**0.001**	↓	**0.000**	**0.000**

Note: Significant differences ($p < 0.05$) between survey periods are in green. For net change, the direction of the arrow indicates whether there was a net forest area loss (↓) or gain (↑).

- analysis of variance (ANOVA) to detect interactions between climatic domain and year (Table 5);
- restricted maximum likelihood (REML) analysis as a more robust tool for assessing differences and interactions assuming unequal variances of the sample populations (Table 6).

THE AREA IN FOREST LAND USE DECLINED BETWEEN 1990 AND 2005

Figure 9 shows the estimated forest area by region in 1990, 2000 and 2005, and Figure 10 shows the estimated forest area by climatic domain for the same years. Total forest area in 2005 was 3.8 billion ha, which is approximately 30 percent of the global land area. There was a net reduction in the global forest area between 1990 and 2005 of 66.4 million ha, or 1.7 percent.

GLOBAL FOREST LOSS AND GAIN

Worldwide, the gross reduction in forest land use was 9.5 million ha per year between 1990 and 2000 and 13.5 million ha per year between 2000 and 2005. This reduction was partially offset by gains in forest area through afforestation and natural forest expansion of 6.8 million ha per year between 1990 and 2000 and 7.3 million ha per year between 2000 and 2005. Thus, the rate of annual net forest loss increased significantly ($p < 0.05$) from 2.7 million ha between 1990 and 2000 to 6.3 million ha between 2000 and 2005 (Table 7). Figures 11 and 12 show these changes by geographic region and climatic domain.

REGIONAL DIFFERENCES IN FOREST LOSS AND GAIN

In South America, significant forest conversion to other land uses occurred in both survey periods: 2.8 million ha per year between 1990 and 2000 and 4.3 million ha per year between 2000 and 2005. In Africa, there were statistically significant net annual forest area losses of 1.1 million ha between 1990 and 2000 and 2.7 million ha between 2000 and 2005.

TABLE 5
ANOVA test for annual net forest area change, by climatic domain and year

Source	Type III SS	df	Mean squares	F-ratio	p-value
Climatic domain	1.096	3	0.365	237.686	0.000
Year	0.053	1	0.053	34.678	0.000
Climatic domain * year	0.164	3	0.055	35.499	0.000
Error	40.162	26124	0.002		

TABLE 6
REML results for annual net change by climatic domain and survey period (1990–2000 and 2000–2005)

Effect	Effect level	Estimate	Standard error	df	t	p-value
Climatic domain	Boreal	0.003	0.002	26 123	1.083	0.279
	Subtropical	0.002	0.002	26 123	0.962	0.336
	Temperate	0.002	0.002	26 123	0.810	0.418
	Tropical	-0.007	0.002	26 123	-2.879	0.004
Year		0.000	0.000	26 123	0.346	0.729
Climatic domain * year	Year * boreal	0.000	0.000	26 123	7.217	0.000
	Year * subtropical	0.000	0.000	26 123	1.638	0.101
	Year * temperate	0.000	0.000	26 123	1.667	0.095
	Year * tropical	0.000	0.000	26 123	-3.069	0.002

FIGURE 9
Forest area by region, 1990, 2000 and 2005

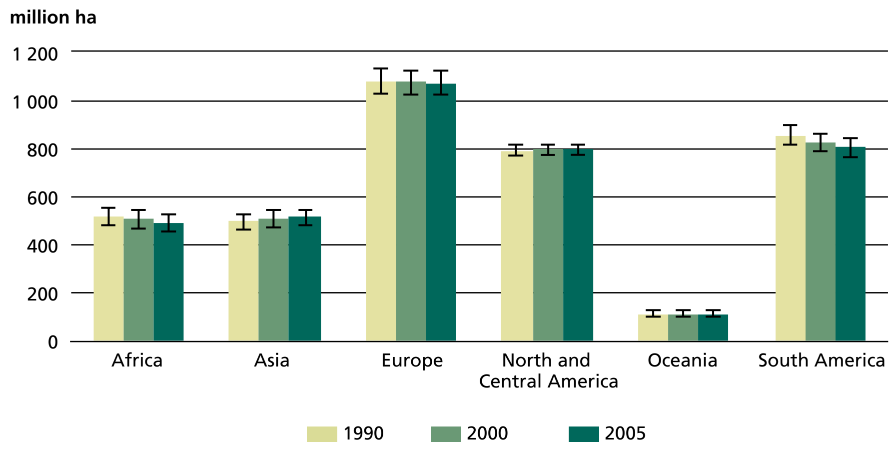


FIGURE 10
Forest area by climatic domain, 1990, 2000 and 2005

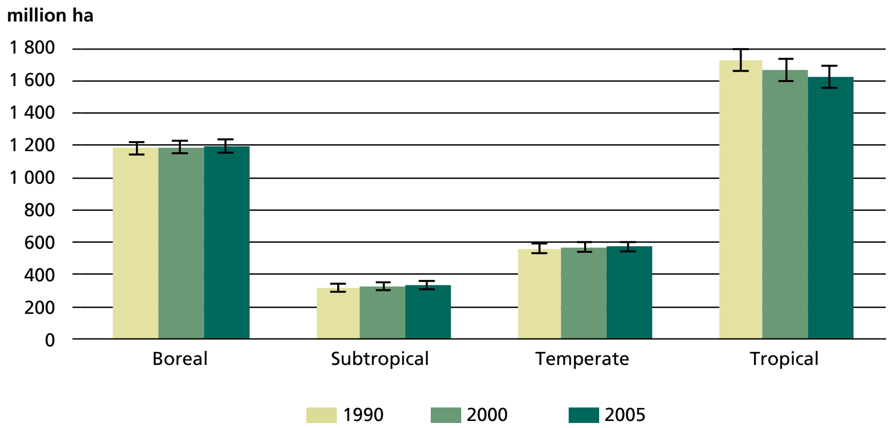


TABLE 7
Mean annual net forest area change and 95 percent confidence intervals between survey periods for FRA regions and FAO climatic domains

	Mean change ('000 ha)		95% confidence interval ('000 ha)		Confidence interval (%)	
	1990–2000	2000–2005	1990–2000	2000–2005	1990–2000	2000–2005
Region						
Africa	-1 091	- 2712	306	560	28	21
Asia	1 419	1 367	564	703	40	51
Europe	-437	-638	303	578	69	91
North and Central America	323	55	190	287	59	522
Oceania	-101	-61	87	136	86	224
South America	-2 779	-4 275	516	863	19	20
Total	**-2 666**	**-6 264**	**902**	**1 410**	**34**	**23**
Climatic zone						
Boreal	776	1 153	565	1 088	73	94
Subtropical	1 212	902	295	380	24	42
Temperate	787	1 152	288	364	37	32
Tropical	-5 648	-9 111	775	1 238	14	14
Total	**-2 873**	**-5 904**	**1 044**	**1 730**	**36**	**29**

Note: Global net change was calculated by summing estimates for FRA regions.

Europe, including the Russian Federation, had a statistically significant net annual loss of forest area of 0.4 million ha between 1990 and 2000 and 0.6 million ha between 2000 and 2005. Oceania had a significant net annual forest loss of 0.1 million ha between 1990 and 2000 and no significant change in forest area between 2000 and 2005. There

FIGURE 11
Gross gains and losses and net changes in forest area, by FRA region, 1990–2000 and 2000–2005

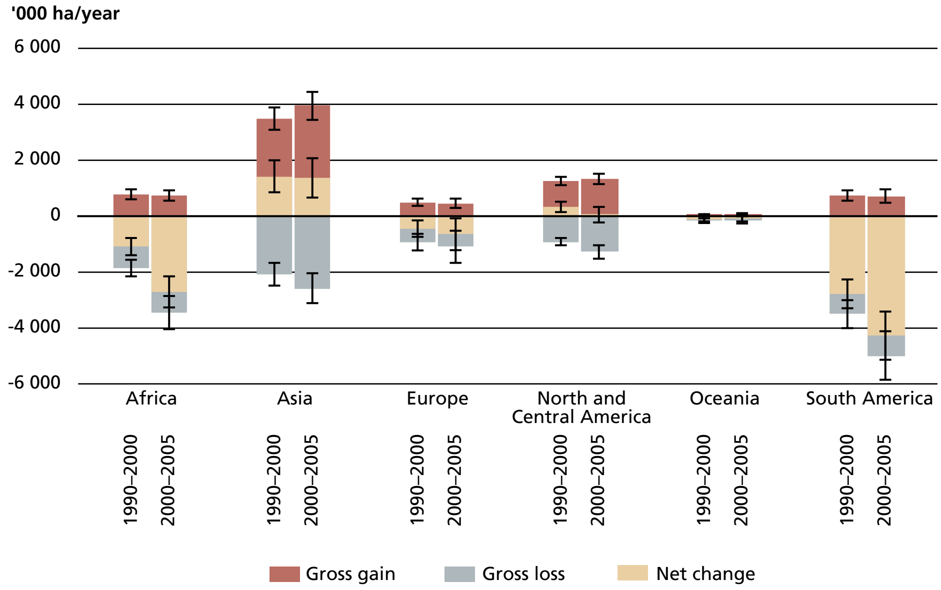
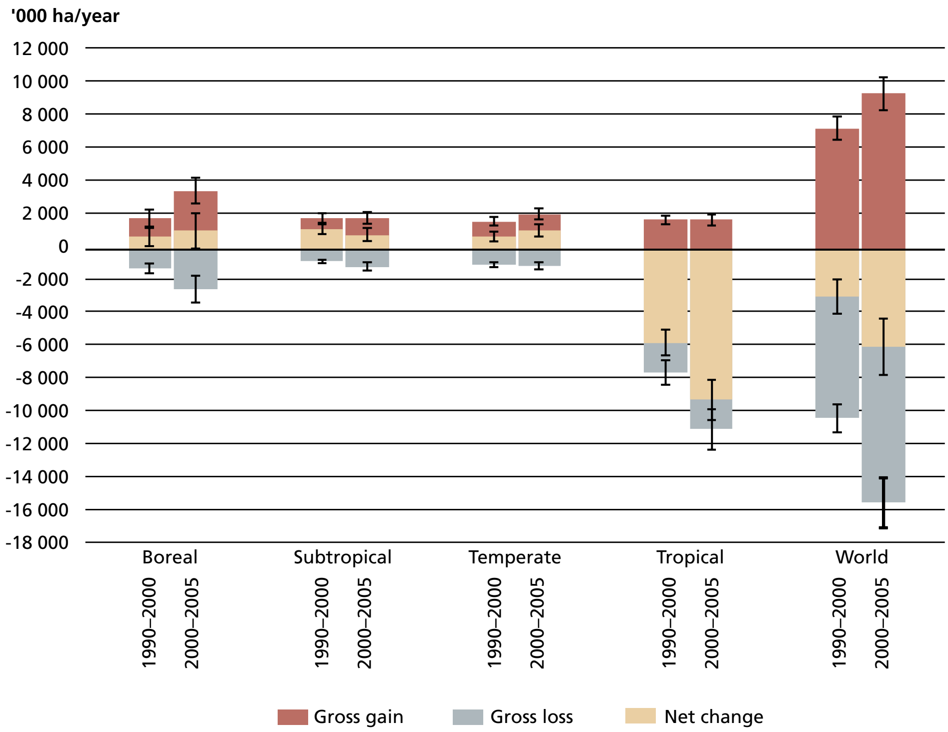


FIGURE 12
Gross gains and losses and net changes in forest area, by FAO climatic domain, 1990–2000 and 2000–2005



was a significant mean annual net gain in forest area in North America between 1990 and 2000 of 0.3 million ha, but there was no significant net change between 2000 and 2005. In Asia, there were significant mean annual net gains in forest area of 1.4 million ha between 1990 and 2000 and 1.4 million ha between 2000 and 2005.

Net forest loss was highest in the tropical climatic domain in both time periods: 5.6 million ha per year between 1990 and 2000 and 9.1 million ha per year between 2000 and 2005.

There were significant net annual gains in forest area in the temperate climatic domain of 0.8 million ha between 1990 and 2000 and 1.2 million ha between 2000 and 2005.

In the boreal climatic domain there were significant net annual gains in forest area of 0.8 million ha between 1990 and 2000 and 1.2 million ha between 2000 and 2005. The high coefficient of variation in these estimates, however, indicates a large range in estimates of forest area change, which could be due to problems in the classification of land use and land cover in this zone.

The subtropical climatic domain showed significant net annual gains in forest area of 1.2 million ha between 1990 and 2000 and 0.9 million ha between 2000 and 2005.

DIFFERENCES IN THE ANNUAL RATE OF CHANGE BY REGION AND CLIMATIC DOMAIN

There was a significant interaction between climatic domain and year (Table 5), meaning that the differences between survey periods were not the same across climatic domain types. These differences in the rate of net forest change between time periods were significant in the boreal and tropical climatic domains and insignificant in the subtropical and temperate domains (Table 6). The only climatic domain that showed a net decrease was the tropics, where the annual net change increased from a loss of 5.6 million ha in 1990–2000 to a loss of 9.1 million ha in 2000–2005.

The REML analysis in Table 6 allows for spatial and temporal correlation and unequal variance between populations and may be more robust than ANOVA for the analysis of survey data. REML analysis is used to decrease the chances of committing a Type 1 error when determining the statistical significance of some results (Picquelle and Mier, 2011).

In recent decades the tropics have been considered the largest source of net forest loss. This study confirms that trend and the fact the most of the loss occurred in South America and Africa (Table 7).

COMPARISON WITH OTHER FAO STUDIES

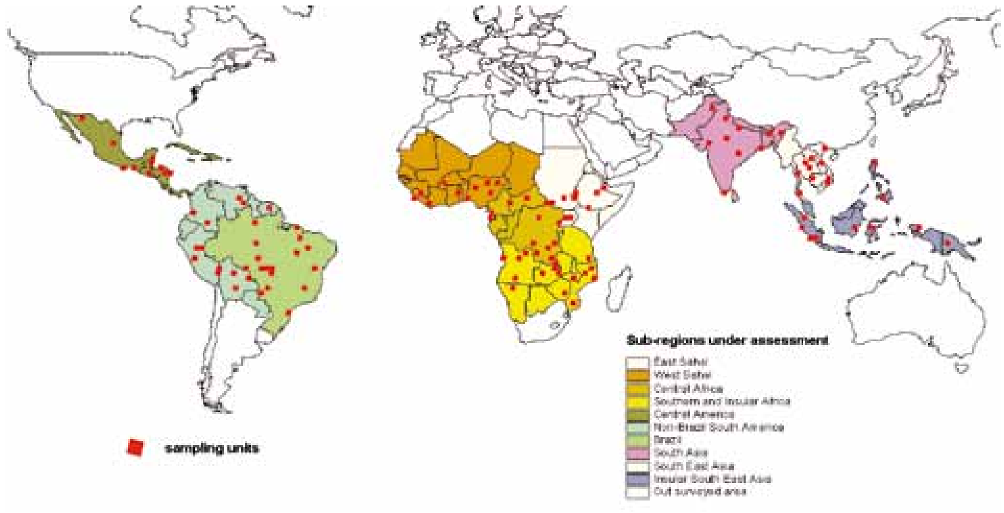
The following section compares estimates of forest area and forest area change made in this project with those derived from previous FAO pantropical remote sensing surveys and those presented in the FRA 2010 tabular reports (using country-supplied data).

Comparison with FRA 2000 pantropical remote sensing data

FAO (2001) conducted a remote sensing-based survey of forest area in the tropics for the years 1990 and 2000; hereafter, that survey is referred to as RSS 2000. RSS 2010 data were aggregated using the same geographic boundaries as those used in RSS 2000 (Figure 13), and the estimates of forest area, gross forest area loss and net forest area change for the years 1990 and 2000 were compared (Figure 14).

Estimates of total forest area and gross forest area loss for the period 1990–2000 were not significantly different ($p < 0.05$) between the two surveys. The difference in estimates of net forest area change was not significantly different in Asia and South and Central America between the two surveys, but it was significantly different ($p < 0.05$) in Africa (Figure 15). RSS 2000 targeted areas of forest cover and did not include samples from non-forest, which could explain why estimates of net forest loss were generally higher in RSS 2000 than in RSS 2010.

FIGURE 13
Distribution of sample points, pantropics, RSS 2000



Note: The 117 sampling units of the survey were selected over the entire pantropical zone following a two-stage random sampling method based on geographical divisions (subregions) and forest cover or forest dominance.

FIGURE 14
Pantropical forest area for 1990 and 2000, as estimated in RSS 2000 and RSS 2010

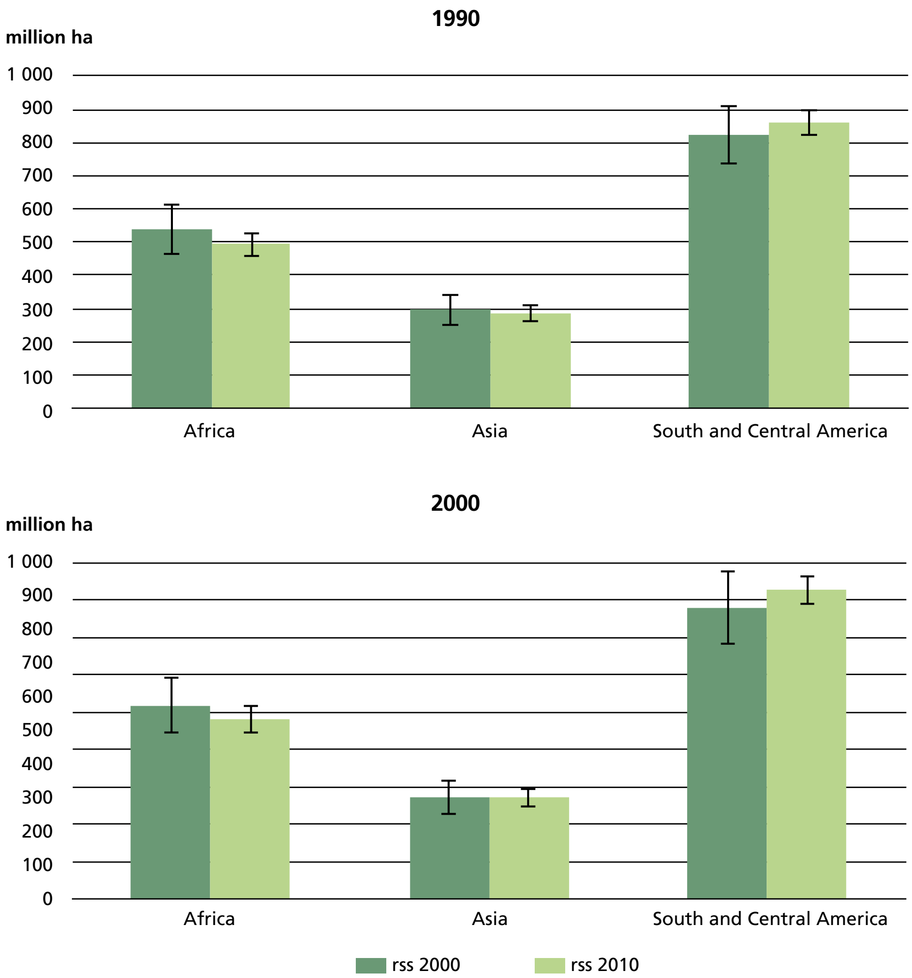


FIGURE 15
Pantropical net annual forest area change between 1990 and 2000, as estimated in RSS 2000 and RSS 2010

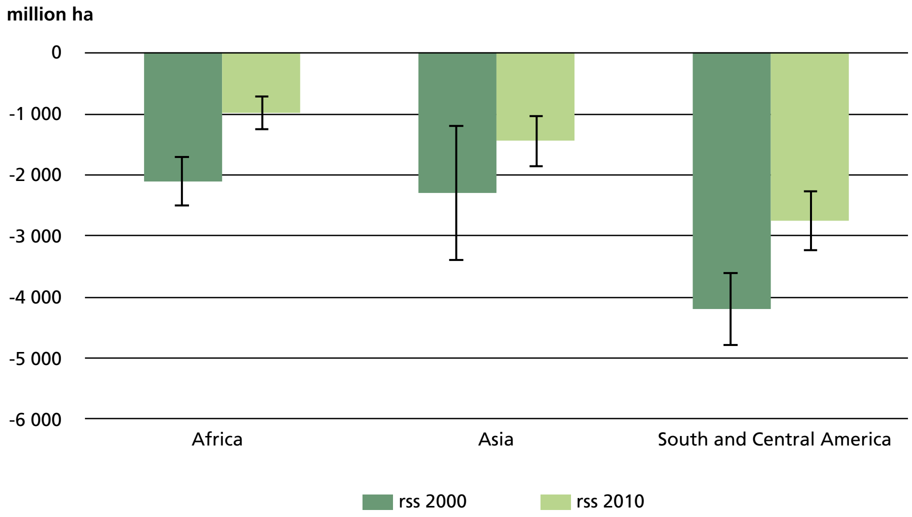
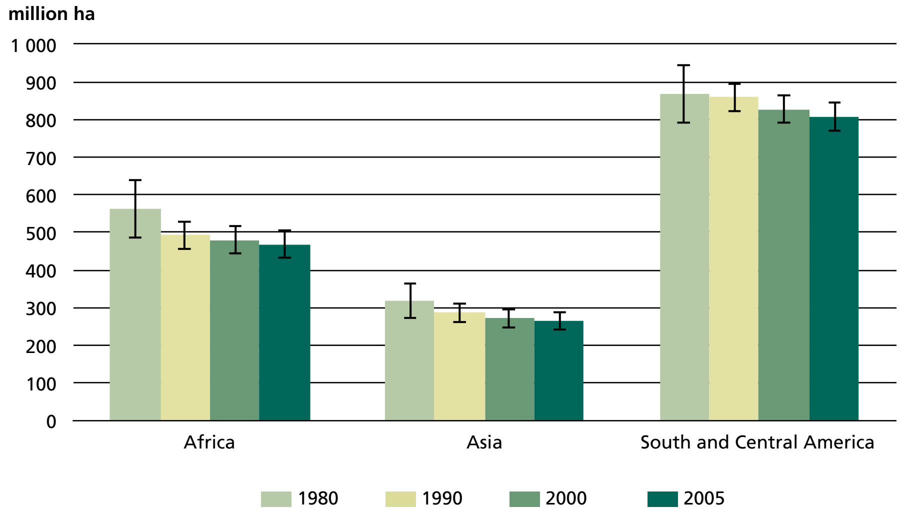


FIGURE 16
Pantropical forest area in 1980, 1990, 2000 and 2005



RSS 2000 consisted of 117 full Landsat scenes (representing a total sample area of 250 million ha) and, in the area coincident to both surveys, RSS 2010 consisted of 3 631 sample sites (representing a total sample area of 36 million ha). The larger number of samples in RSS 2010 increased the precision of its estimates compared with those made in RSS 2000.

Figure 16 shows a complete timeline of tropical forest area estimates, by region, for 1980, 1990, 2000 and 2005 derived from FRA remote sensing surveys. The estimates for 1980 were derived from RSS 2000 and the estimates for 1990, 2000 and 2005 were derived from RSS 2010.

Comparison with FRA 2010 tabular reports

The estimates of forest area and rates of change in RSS 2010 differ from those presented in the tables contained in FRA 2010 for both forest area and annual forest area change. Differences between the "state" (e.g. forest area) and "trend" (e.g. forest area change) of forest land use are complex. In the following section, differences between RSS 2010 and FRA 2010 tabular reports (hereafter referred to as FRA 2010) are examined with respect to several key criteria, including the definition of forest, the reporting methods of both surveys, and the overall quality of the reported information.

Differences in forest area

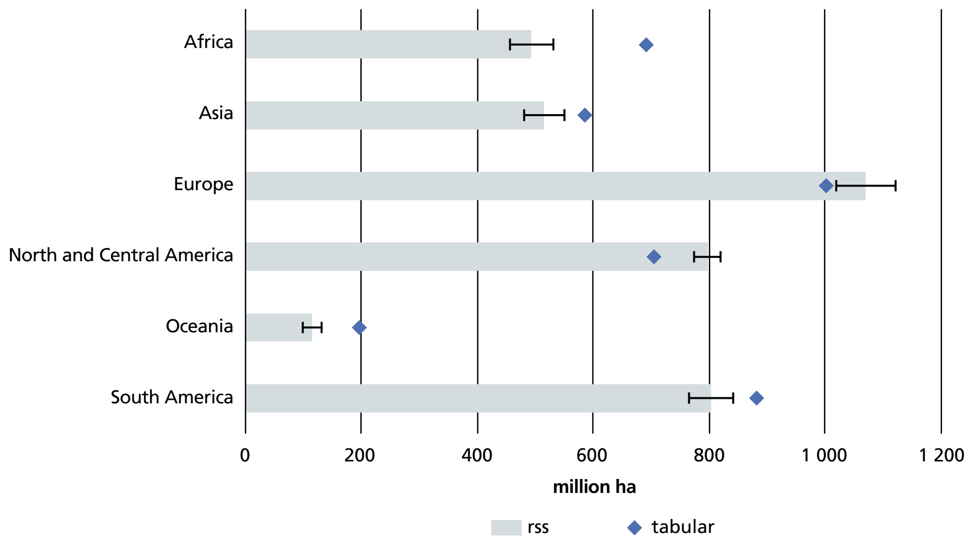
The estimate of forest area in Africa in 2000 was almost 200 million ha (29 percent) greater in FRA 2010 than in RSS 2010 (Figure 17). On a percentage basis, the greatest difference was in Oceania, where the estimated forest area in 2000 was 41 percent (81 million ha) greater in FRA 2010. Similar differences in forest area were observed for 1990 and 2005 estimates.

Differences in forest area estimates between this study and FRA 2010 are likely due to differences in survey and reporting methods and to an issue in remote sensing arising from the definition of forest. The methods used to derive estimates in FRA 2010 vary by country and include the use of national forest inventories, remote sensing-based studies and expert opinion. FRA 2010 country questionnaires had a standard template to improve consistency between countries, but differences between countries in reporting standards still led to inconsistencies in the analysis of both the state and trend of forest area. For example, some countries did not submit completed FRA questionnaires for FRA 2010. For such countries, forest area state and trend were derived from ancillary data sources or previously reported figures (FAO, 2001). Depending on the frequency and standard of reporting, there is a risk that estimates are out of date and of unknown accuracy (Matthews, 2001).

Africa currently has the oldest data, on an area-weighted basis, of all the FRA regions (Ö. Jonsson, personal communication, 2012). The use of outdated information, which required extrapolation, sometimes over decades, to produce estimates for FRA 2010, contributes to the variation observed between forest area estimates in the two studies.

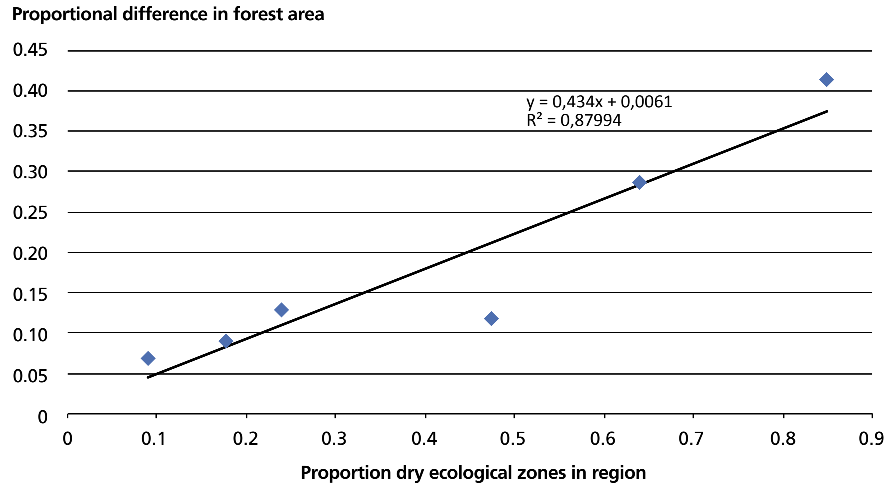
The definition of forest used in both FRA 2010 and RSS 2010 is characterized by a low threshold for tree canopy cover (i.e. > 10 percent), which is difficult to detect using medium spatial resolution satellite imagery and to delineate accurately in the field at anything other than the plot level. Forest area with canopy cover less than 20 percent

FIGURE 17
A comparison of forest area, by region, as reported in FRA 2010 and RSS 2010



Note: Blue dots represent area of forest land use as estimated in FRA 2010, and black bars represent the 95 percent confidence intervals about the mean estimated in RSS 2010.

FIGURE 18
Relationship between proportion of dry climatic domains per region and the proportional difference between FRA 2010 and RSS 2010 forest area estimates for that region



may not be reliably detected from medium spatial resolution satellite imagery such as Landsat. Work is ongoing to determine canopy-cover percentage thresholds classified as forest in RSS 2010 through the incorporation of high spatial resolution imagery at selected locations. More consistent characterization of low-canopy-cover sites could reduce some of the difference between the two methodologies.

To test the theory that difficulty in delineating low-canopy-cover forest (usually in drier forest areas) contributes to differences in forest area estimates between FRA 2010 and RSS 2010, the proportion of dry ecological zone per region was related to the absolute difference in forest area estimates. Figure 18 shows a high degree of correlation between the area of dryland and differences in forest area estimates between FRA 2010 and RSS 2010; uncertainty in estimating dryland forest area, therefore, may contribute to differences in forest area estimates.

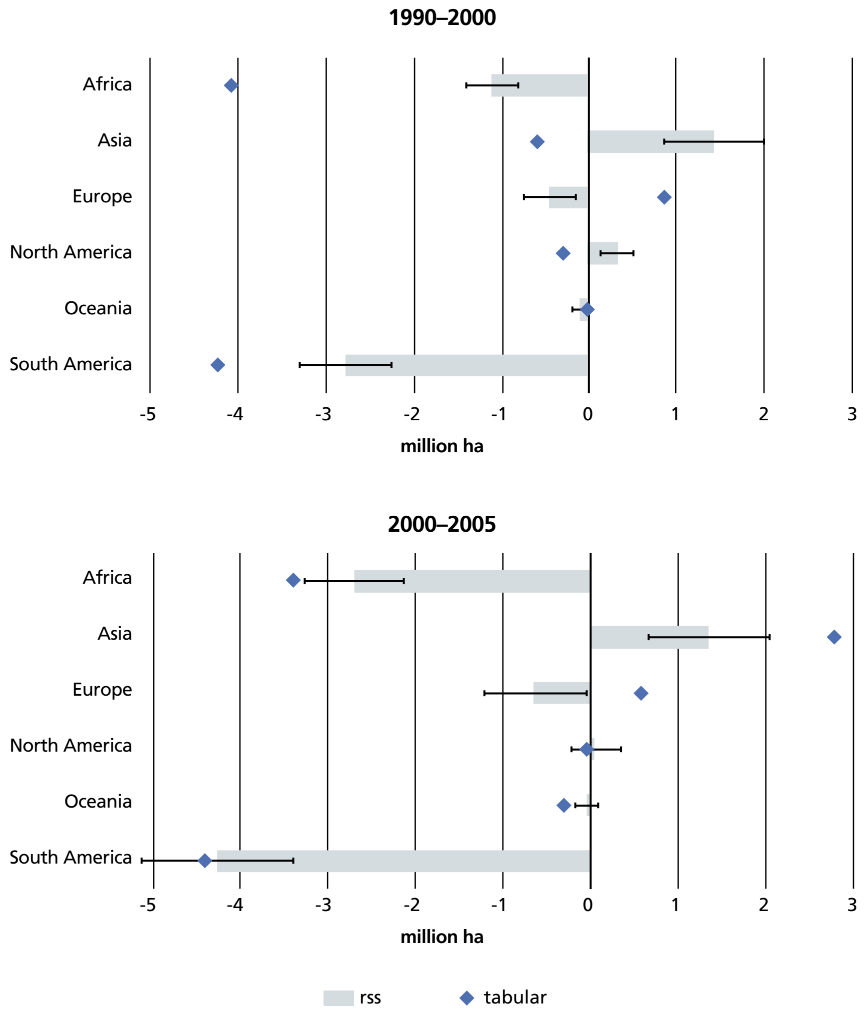
Differences in net forest area change

The estimates of net change in forest area in RSS 2010 also differ from those reported in FRA 2010. Overall net change was much lower in this study (66.4 million ha) than in FRA 2010 (107.4 million ha). The magnitude of the annual rate of change was also different. RSS 2010 results indicate that the annual rate of net forest area loss increased from about 3 million ha in the period 1990–2000 to 6 million ha in the period 2000–2005. FRA 2010, on the other hand, indicated a decrease in the rate of annual net forest loss from 8.3 million ha in 1990–2000 to 4.8 million ha in 2000–2005.

Differences in net change estimates between the two surveys are due largely to uncertainties in forest area and change in Africa, Asia and South America (Figure 19). In the period 1990–2005, RSS 2010 estimated a lower net decrease in forest area in Africa and South America and a higher net increase in forest area in Asia compared with FRA 2010. RSS 2010 indicated a net increase in forest area in Asia in both periods, while FRA 2010 estimated a net decrease in forest area between 1990 and 2000 and a net increase between 2000 and 2005.

It should be noted that FRA 2010 did not report specifically on forest loss as a distinct and separate variable; rather, forest change estimates were derived from the difference between forest area estimates over time. Thus, errors in forest area reporting may be compounded, or they may confound estimates of forest area change.

FIGURE 19
Net change in forest area, RSS 2010 compared with FRA 2010



CAUSES OF LAND-USE CHANGE

The type or cause of land-use change was not assessed in this study as originally planned. The attribution by national experts of land-use types to more detailed classes proved difficult in the time allotted during the review-and-revision workshops. Thus, while the conversion of forest land use to other land uses and vice versa can be analysed readily, RSS 2010 results do not indicate whether forest losses are attributable to specific uses (e.g. pastureland or cropland). Likewise, gains in forest area could be due to natural expansion or the establishment of planted forests.

Existing scientific literature can be used to gain insight into the causes of forest land-use conversion. Survey results re-affirmed that tropical zones account for the largest portion of global net forest loss. Gibbs *et al.* (2010) re-analysed RSS 2000 data and estimated that the total net increase in agricultural area between 1980 and 2000 in the tropics was greater than 100 million ha, nearly 80 percent of which came from previously intact or disturbed forest land use. Given the sustained and increasing demand for agricultural products for food and energy, it is likely that forest conversion to other land uses in the tropics in the period 2000–2005 was also due predominantly to the expansion of agriculture (Lambin and Meyfroidt, 2011).

RSS 2010 results indicate that forest area increased in the temperate climatic domain, likely due to increases in planted forests in temperate Asia. Liu and Tian

(2010) document a large increase (51.8 million ha) in forest area in China due to the establishment of planted forests, a process that began in the 1950s and continues today. FRA 2010 confirmed in part this finding for China, reporting an increase in forest area of about 2.5 million ha annually – for a total of 49.7 million ha – between 1990 and 2010.

RSS 2010 results also show an increase in forest area in the boreal climatic domain, although this increase is a surprise and is more difficult to explain. It may be due to forest regrowth on abandoned farmland in parts of the former Soviet Union: Kuemmerle *et al.* (2010), for example, estimate the natural expansion rate on abandoned farmland in Ukraine since 2000 at 8 600 ha per year. Similar rates of natural expansion of forest may be occurring on the nearly 26 million ha of abandoned farmland in the Russian Federation, Belarus and Kazakhstan (Lambin and Meyfroidt, 2011).

Another possible explanation for the detected increase in forest area in the boreal climatic domain could be the misidentification of burned areas as non-forest land use in earlier time periods. In Canada, a largely automated review and revision of land-use classifications was undertaken using the large Canadian National Fire Database (Stocks *et al*., 2002) to identify burned areas and reclassify other land cover to forest land use where a fire was considered to be the cause of forest loss. The Canadian National Fire Database includes fires greater than 200 ha in size and represents about 97 percent of the total area burned annually in Canada (Stocks *et al*., 2002). The mislabelling of small fires as non-forest land use or any discrepancies between the RSS 2010 land-cover detection and the Canadian National Fire Database may have contributed to an artificial increase in forest land-use area as burnt areas regenerate.

ACCURACY ASSESSMENT

A formal accuracy assessment of the land-use classification was not performed as part of this study. It is difficult to find data sources of higher spatial resolution, appropriate temporal resolution or greater reliability, especially globally, against which to check the automatically classified and expert-revised land-use labels. A comparison of the automatically classified land-cover labels before and after expert review and revision indicated overall agreement of 77–81 percent (Lindquist *et al.*, submitted). Comparisons of expert-revised land-cover classifications with high spatial resolution satellite imagery for selected sites in the Russian Federation indicated that expert revision could yield accuracies of nearly 100 percent for a forest/other land dichotomous classification scheme (Bartolev, 2012 unpublished data).

It is expected that land cover will reflect the underlying land use in most instances; therefore, the accuracies achieved by the methods used should provide an indication of the overall accuracy of estimates. However, the exceptions to the land-cover/land-use equivalence generalization are important and significant. In the future, further effort will be directed at devising a method for assessing more thoroughly the accuracy of the land-use classification.

5. Conclusion

This is the first survey of its kind to measure, in a systematic way, losses and gains in forest land use between 1990 and 2005 at the global, regional, climatic domain and ecological zone levels of aggregation. The results presented in this report indicate that forest conversion to other land uses is most prevalent in the tropical climatic domain and, within this domain, in South America. Other climatic domains were remarkably stable in terms of net forest land-use change over the period 1990–2005.

The systematic survey design permitted estimates of gross forest area gains and losses and net changes in forest area, each with an estimate of precision. The exhaustive review-and-revision process by national-level forestry and remote sensing experts made possible the correction of classification errors and the identification of land uses not discernible from remotely sensed data sources alone, and provided an improved ecological context for the monitoring of forest cover and forest land-use change globally.

INTEGRATION OF COARSE RESOLUTION SATELLITE IMAGERY TO HELP CLASSIFICATION

The survey benefited from the use of global coarse spatial resolution datasets to both normalize and classify the relatively finer spatial resolution Landsat samples. Although coarse spatial resolution satellite imagery is often unsuitable as a stand-alone data source for detecting change, several studies have shown the effectiveness of using such data for the purpose of selecting training data for land-cover classifications at finer spatial resolutions. For example, Hansen *et al.* (2008) showed the utility of using coarse spatial resolution data from the MODIS VCF product to delineate potential training sites for a forest/non-forest classification in Central Africa. Similar methods have also been applied successfully in the Brazilian Legal Amazon (Broich *et al*., 2009), Indonesia (Broich *et al*., 2011), and the boreal region of the Russian Federation (Potapov *et al*., 2008; Potapov, Turubanova and Hansen, 2011).

IMPORTANCE OF VISUAL REVIEW AND REVISION OF CLASSIFICATION

Visual control and correction was an important part of the land-cover and land-use classification processes and had a large impact on the final results. A comparison of the initial results from the automated land-cover classification and final reviewed-and-revised results for the tropics indicated that about 20 percent of the polygon labels were revised by national experts (Raši *et al.*, 2011). Similar results were obtained for sites in the boreal, temperate and subtropical domains (Lindquist *et al*., submitted). The visual refinement process also had a notable effect on estimates of forest area and forest area change: for Southeast Asia, for example, the net rate of change in tree cover (loss) from 1990–2000 was assessed at 0.9 percent before and 1.6 percent after visual control (Raši *et al.*, 2011).

THE UTILITY OF LANDSAT FOR GLOBAL MONITORING

Land-cover classification and change detection methods that leverage available data from the current generation of Landsat sensors is critical for maintaining a record of land-cover changes until the new generation of sensors comes online. The Landsat programme has the longest continuous time-series of similar remotely sensed Earth observations and is a critical component in the analysis of change in land cover and land use since the 1970s. Landsat 7, the latest sensor, was launched in 1999 but suffered a mechanical failure in May 2003 that created no-data gaps in the across-track scan line covering 23 percent of each image (Williams, Goward and Arvidson, 2006). Sampling methods, such as those described in this report, are a suitable use of the currently available Landsat image acquisitions and should be used to leverage the large amounts of information freely available in the Landsat archive (Woodcock *et al*., 2008).

ESTABLISHMENT OF GLOBAL NETWORKS

The project established two very important global networks. One was the global survey grid, which will be updated with data from 2010 as part of the next FRA (to be released in 2015). The second and perhaps more important network comprises the many national experts who participated in the survey and who remain important points of contact and sources of forest remote sensing and land-use expertise in individual countries.

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Annex 1
Country-specific review-and-revision methodologies

Every effort has been made to produce consistent results at a global scale. Some countries, however, used unique methods to review and revise land-cover and land-use classifications. Those methods are described here.

CANADA

Data for Canada were derived using the classification methodology described in the main body of this report but applied across the Canadian National Forest Inventory (NFI) photo-plot grid system (Gillis, Omule and Brierley, 2005). The NFI uses 2 km × 2 km plots with 20 km horizontal and vertical spacing (i.e. a 20 km systematic grid), producing more than 18 000 individual plots. For the purposes of RSS 2010, a 25 percent sample of the plots (i.e. every fourth plot) was selected for initial analysis (Figure 1). In total, 4 052 2 km × 2 km plots were analysed across Canada.

At each plot location, level-1 segments from imagery captured in 2000 were directly assigned land-cover labels based on the Canadian Earth Observation for Sustainable Development of Forests (EOSD) dataset (Wulder *et al.*, 2006). The EOSD dataset is a 25 m spatial resolution, Landsat-based, 23-class land-cover classification for the forested areas of Canada. The 23 EOSD classes were aggregated into the simple 5-class legend, and level-1 segments for 2000 were assigned a value based on the majority land cover of the underlying EOSD data. The full methodology, as described in the main body of this report, was used where no EOSD data existed (i.e. in largely non-forested portions of Canada) and to classify 1990 and 2005 segments.

The initial conversion of land cover to land use was completed following the survey conversion rules, as described in the main body of this report. Next, a series of automated re-coding procedures was implemented in the review-and-revision phase of land-use validation. These procedures involved re-coding polygons to forest land use in cases where commercial timber harvest activity was indicated from NFI photo-plot data, where a forest fire occurred during the period of analysis (as indicated in the Canadian National Fire Database; Stocks *et al.*, 2002), or where no known deforestation (on the basis of NFI land-use and deforestation information) had occurred. Remaining sites were examined by image interpreters to ensure the accuracy of the final land-use classification.

Parameter estimates were calculated separately for Canada and integrated into analyses of FRA regions and FAO climatic domains.

RUSSIAN FEDERATION

The Russian Federation used a stratified sample of 300 RSS sample sites to estimate forest area and forest area change for the three survey periods. A total of 1 961 complete RSS sample sites were contained within the Russian Federation. Landsat data were available for 1 219 of these for all three time periods; this incomplete coverage is due to the lack of satellite data acquisitions for the eastern part of the Russian Federation in 1990. Although all 1 961 sample sites were processed to the extent possible using the methods described in the main body of this report, expert review and revision of all sample sites in the Russian Federation was not possible in the timeframe of the study.

Cloud-free, seasonal 250 m spatial resolution data from MODIS were used, along with vegetation change indices, to create 23 strata according to percentage forest cover and amount of indicated change in forest cover. A probability-based selection process was implemented to select the final plots for review and revision based on a minimum separating distance (i.e. plots were preferred to be further apart within any single stratum) and minimum number (ten) per stratum. A total of 282 RSS sites were expertly interpreted for land-cover and land-use classification.

The parameter estimates and statistical variance of the stratified sample were incorporated with those of the systematic sample for Europe and used in analyses of the boreal climatic domain.

UNITED STATES OF AMERICA

RSS results for the United States of America were derived from the National Land Cover Dataset (NLCD) (Vogelmann *et al*., 2001; Homer *et al*., 2004). The NLCD is a 21-class land-cover product for the conterminous United States based on Landsat satellite data. The 21 classes were reduced to the five simple land-cover classes required for RSS 2010. Level-2 segments for 1990, 2000 and 2005 were assigned land-cover labels directly from the NLCD dataset for each survey period. Land-cover labels were adjusted to land use using the automated conversion rules described in the main body of this report. A probability-based sample of sites, by FAO climatic domain, was selected for review and revision for continental United States and Alaska. At each review-and-revision site, the accuracy of the land-use call was evaluated against the NLCD and high-resolution aerial photography. The results of the accuracy assessment were used to adjust the overall area of land-use category for the United States in its entirety and for each FAO climatic domain.

Annex 2

Survey sites processed vs analysed

The table below lists, by region or country-specific grouping, the number of sample sites processed (grand total), analysed and not analysed. The main reason that survey sites were not analysed was missing data in one or more time periods due to cloud cover, a lack of satellite image acquisitions, or other data anomalies.

Region/country	Analysed	Not analysed	Grand total
Africa	2 322	196	2 518
Asia	2 863	184	3 047
Canada	3 737	315	4 052
Europe	625	55	680
Oceania	769	29	798
Russian Federation	282	1 679	1 961
South America	1 372	129	1 501
North & Central America	1 096	126	1 222
Grand Total	**13 066**	**2 713**	**15 779**

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Summary of national and regional review-and-revision workshops

Area of interest	Location	Date	No. countries	No. experts	Female	Male
Brazil	São José dos Campos	September 2009	1	2	0	2
Central Africa	Brazzaville	February 2010	8	16	1	15
North America	Salt Lake City	March 2010	3	3	1	2
South Africa	Cape Town	March 2010	8	16	3	13
West Europe	Rome	March 2010	14	14	3	11
Central America	Panama City	July 2010	7	12	5	7
Southeast Asia	Bangkok	August 2010	14	23	5	18
East Asia	Beijing	September 2010	3	16	3	13
South America	Valdivia	November 2010	7	14	2	12
France	Nogent	November 2010	1	1	0	1
East Africa	Nairobi	December 2010	6	11	1	10
West Africa	Dakar	March 2011	13	18	1	17
New Zealand	Rome	March 2011	1	1	0	1
Australia	Canberra	April 2011	1	2	1	1
East Europe	Budapest	May 2011	9	14	1	13
Ireland/Latvia	Teleconference	May 2011	2	2	0	2
Sudan	Khartoum	May 2011	1	18	5	13
Brazil	Campinas	June 2011	1	9	3	6
Italy	Rome	June 2011	1	5	1	4
West Asia, North Africa	Rome	July 2011	5	5	0	5
Russian Federation	Moscow	September 2011	1	2	0	2
Total			**107**	**204**	**36**	**168**

Annex 4
Details of calculation

1. For every sample site, the following variables were extracted from the PostGreSQL database:
   - tile unique ID (*rss_id*)
   - latitude (*lat*) and longitude (*lon*) of the centre of the tile
   - climatic domain (*domain*)
   - region (*continent*)
   - total tile area (*total*)
   - water area (*water*)
   - no data area (*nodata*)
   - forest area in 1990, 2000 and 2005 (*forest90, forest00, forest05*)
   - area of gains and losses of forest in 1990-2000 and 2000-2005 (*gain9000, loss9000, gain0005, loss0005*)
   - Julian date of image acquisition for 1990, 2000, 2005 (*jdate90, jdate00, jdate05*)

2. Then, the following variables were calculated:
   - Area of land within the tile (*gla*)

Eq. 1 $$gla = total - water - nodata$$

   - Latitude correction factor (*corrlat*)

Eq. 2 $$\begin{cases} if\ lat \leq 60° \ then\ corrlat = \cos(lat) \\ if\ lat > 60° \ then\ corrlat = 2 * \cos(lat) \end{cases}$$

NB: The number of samples was reduced to include only even degrees of longitude above 60 degrees latitude (Figure 1 shows the thinning of samples at high northern latitudes).

   - Weight of the sample i (w_i)

Eq. 3 $$w_i = \frac{gla_i * corrlat_i}{\Sigma_j\, gla_j * corrlat_j}$$

   - Proportion of forest in 1990, 2000 and 2005 (*pfor90, pfor00, pfor05*)

Eq. 4 $$\begin{cases} pfor90 = \dfrac{forest90}{gla} \\ pfor00 = \dfrac{forest00}{gla} \\ pfor05 = \dfrac{forest05}{gla} \end{cases}$$

- Annualized proportion of gains, losses and net change for 1990–2000 (*pagain9000*, *paloss9000*, *panet9000*)

Eq. 5
$$\begin{cases} pagain9000 = \dfrac{gain9000}{gla * (jdate00 - jdate90)} \\ paloss9000 = \dfrac{loss9000}{gla * (jdate00 - jdate90)} \\ panet9000 = pagain9000 - paloss9000 \end{cases}$$

NB: *pagain0005*, *paloss0005* and *panet0005* are calculated in the same way

3. For any subset S of samples (e.g. one climatic domain), average value ($\bar{x}$) and standard deviation (std) of *pfor90, pfor00, pfor05, pagain9000, paloss9000, panet9000, pagain0005, paloss0005* and *panet0005* were calculated with the survey package of R[3] using the following formula:

Eq. 6
$$\bar{x} = \frac{\Sigma_{i \in S} W_i * x_i}{\Sigma_{i \in S} W_i}$$

Eq. 7
$$std = \sqrt{\frac{\Sigma_{i \in S} W_i * (x_i - \bar{x})^2}{\Sigma_{i \in S} W_i}}$$

4. Final values (e.g. of annual loss in forest area between 1990 and 2000 in a given climatic domain) were obtained by multiplying the average and the standard deviation by the area of the region (*A*):

Eq. 8
$$loss = \overline{paloss9000} * A \pm 1.96 * \frac{std(paloss9000)}{\sqrt{N}} * A$$

[3] http://cran.fhcrc.org/web/packages/survey/index.html.

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Global forest land-use change 1990–2005

This report presents the key findings on forest land use and land-use change between 1990 and 2005 from FAO's 2010 Global Forest Resources Assessment Remote Sensing Survey. It is the first report of its kind to present systematic estimates of global forest land use and change.

The ambitious goal of the Remote Sensing Survey was to use remote sensing data to obtain globally consistent estimates of forest area and changes in tree cover and forest land use between 1990 and 2005. Overall, it found that there was a net decrease in global forest area between 1990 and 2005, with the highest net loss in South America. While forest area increased over the assessment period in the boreal, temperate and subtropical climatic domains, it decreased by an average of 6.8 million hectares annually in the tropics. The survey estimated the total area of the world's forests in 2005 at 3.8 billion hectares, or 30 percent of the global land area.

This report is the result of many years of planning and three years of detailed work by staff at FAO and the European Commission Joint Research Centre, with inputs from technical experts from more than 100 countries. Many of these contributors now constitute a valuable global network of forest remote sensing and land-use expertise.

ISBN 978-92-5-107399-5 ISSN 0258-6150
9 789251 073995
I3110E/1/11.12