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

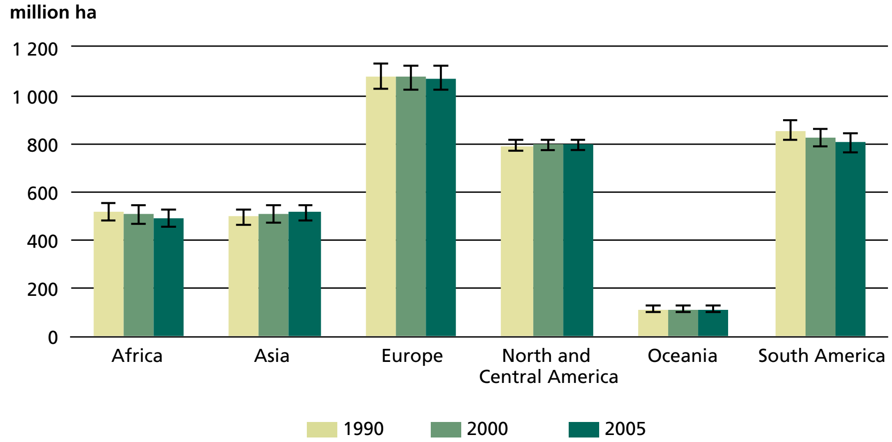


FIGURE 10
Forest area by climatic domain, 1990, 2000 and 2005

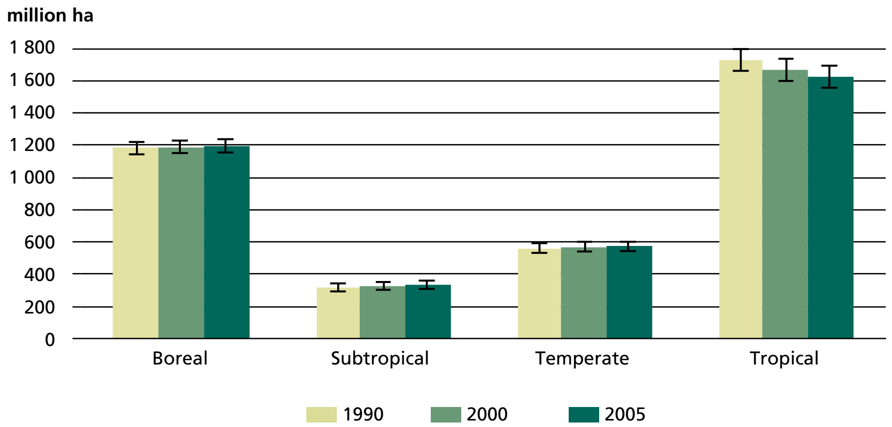


TABLE 7
Mean annual net forest area change and 95 percent confidence intervals between survey periods for FRA regions and FAO climatic domains

	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

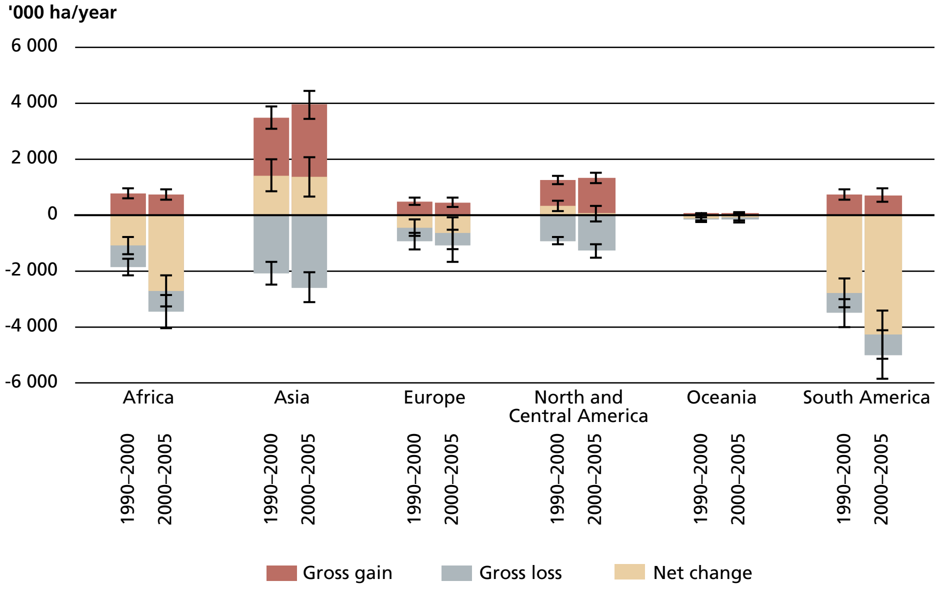
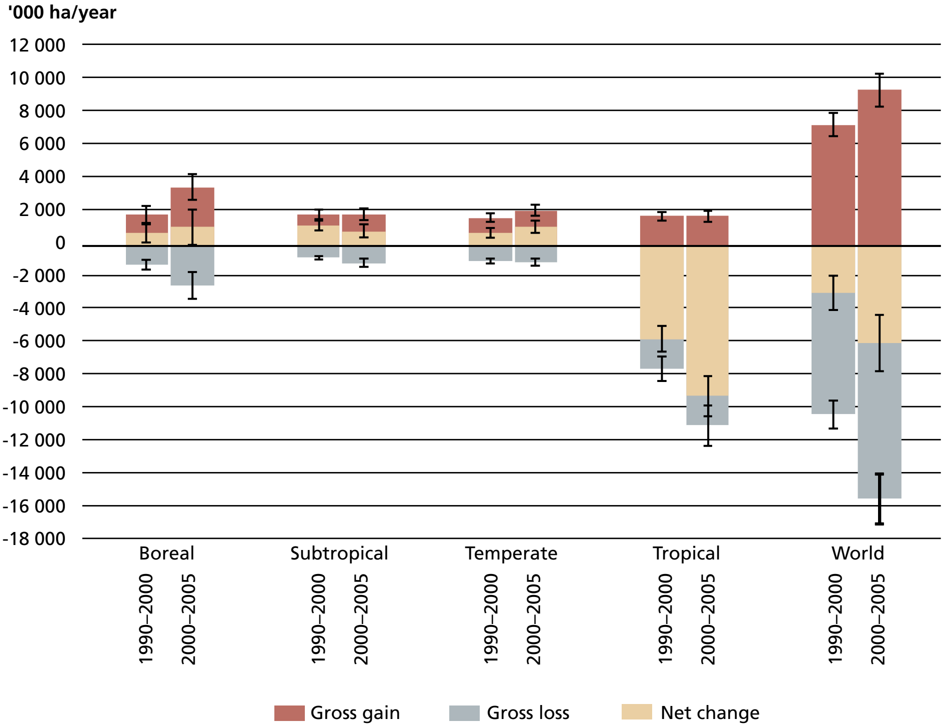


FIGURE 12
Gross gains and losses and net changes in forest area, by FAO climatic domain, 1990–2000 and 2000–2005



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

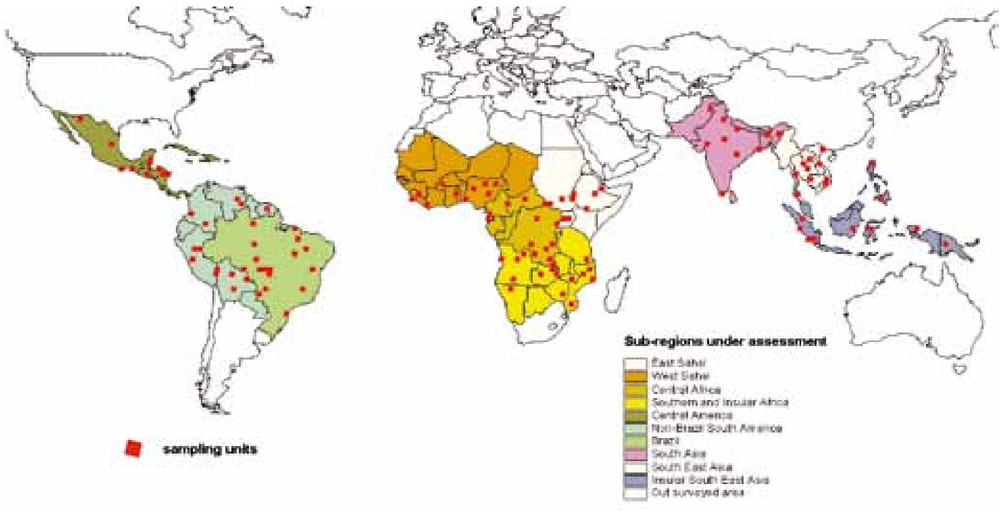
The following section compares estimates of forest area and forest area change made in this project with those derived from previous FAO pantropical remote sensing surveys and those presented in the FRA 2010 tabular reports (using country-supplied data).

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

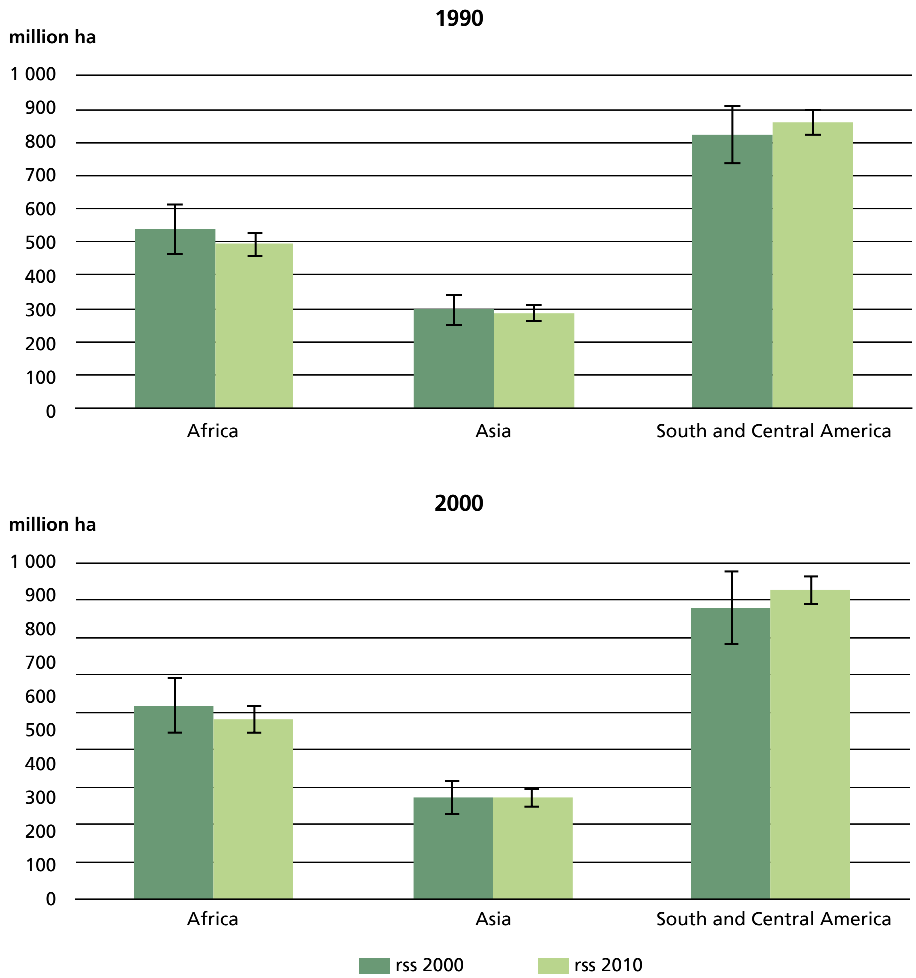


FIGURE 15
Pantropical net annual forest area change between 1990 and 2000, as estimated in RSS 2000 and RSS 2010

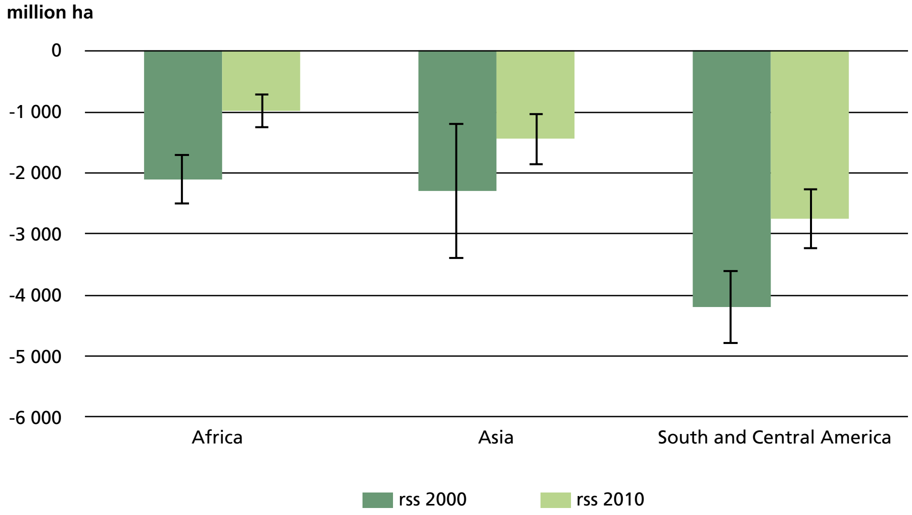
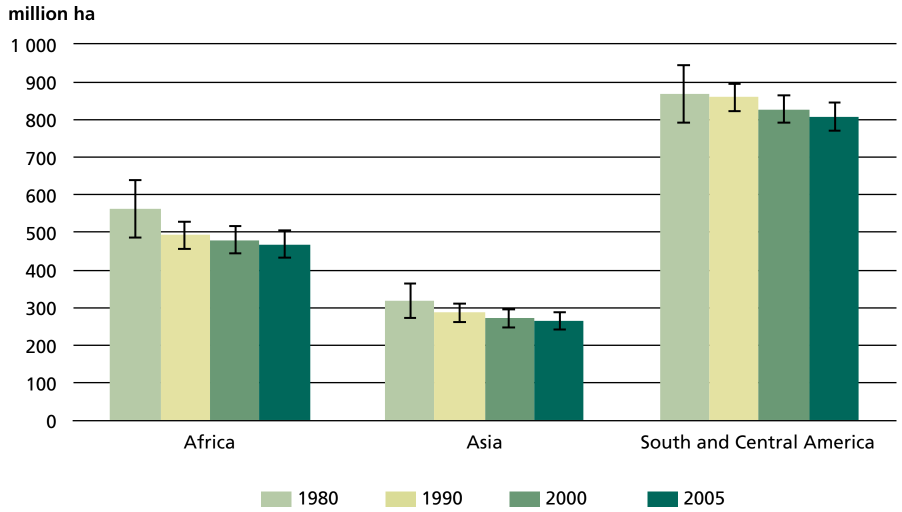


FIGURE 16
Pantropical forest area in 1980, 1990, 2000 and 2005



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

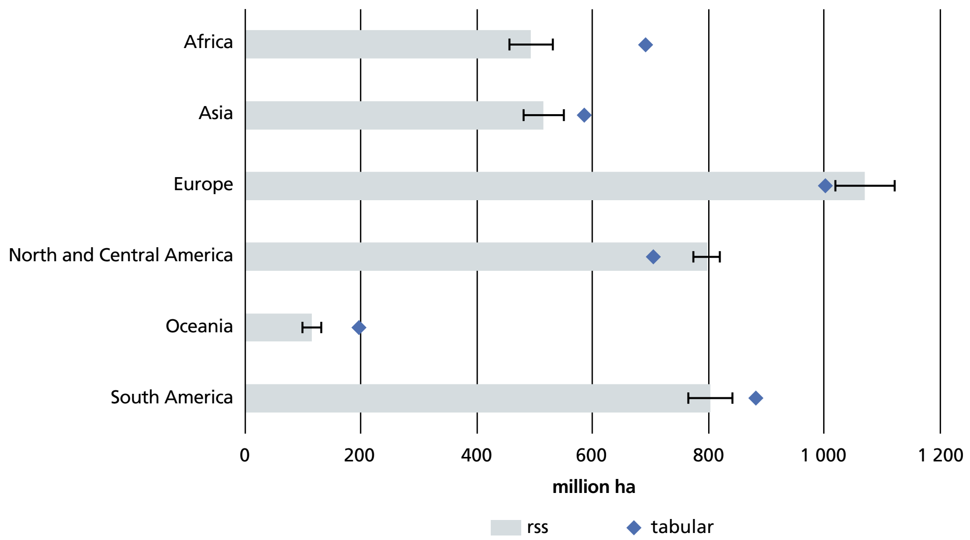
The estimate of forest area in Africa in 2000 was almost 200 million ha (29 percent) greater in FRA 2010 than in RSS 2010 (Figure 17). On a percentage basis, the greatest difference was in Oceania, where the estimated forest area in 2000 was 41 percent (81 million ha) greater in FRA 2010. Similar differences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

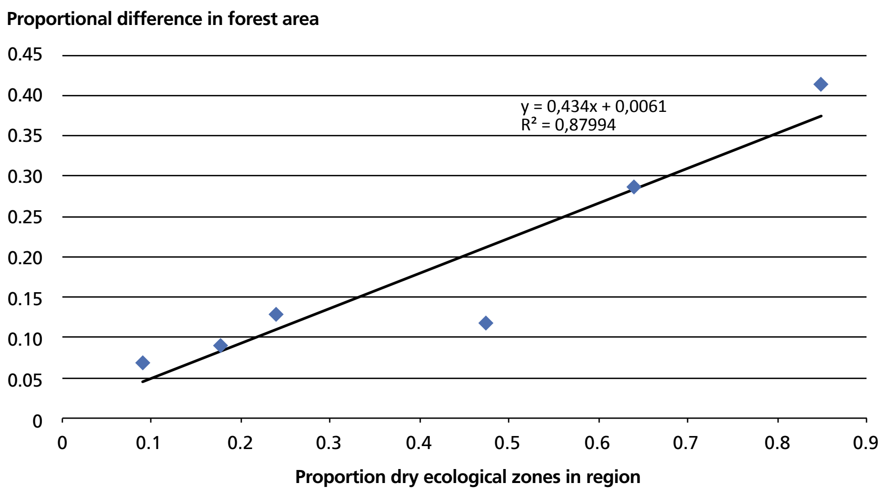
The definition of forest used in both FRA 2010 and RSS 2010 is characterized by a low threshold for tree canopy cover (i.e. > 10 percent), which is difficult to detect using medium spatial resolution satellite imagery and to delineate accurately in the field at anything other than the plot level. Forest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

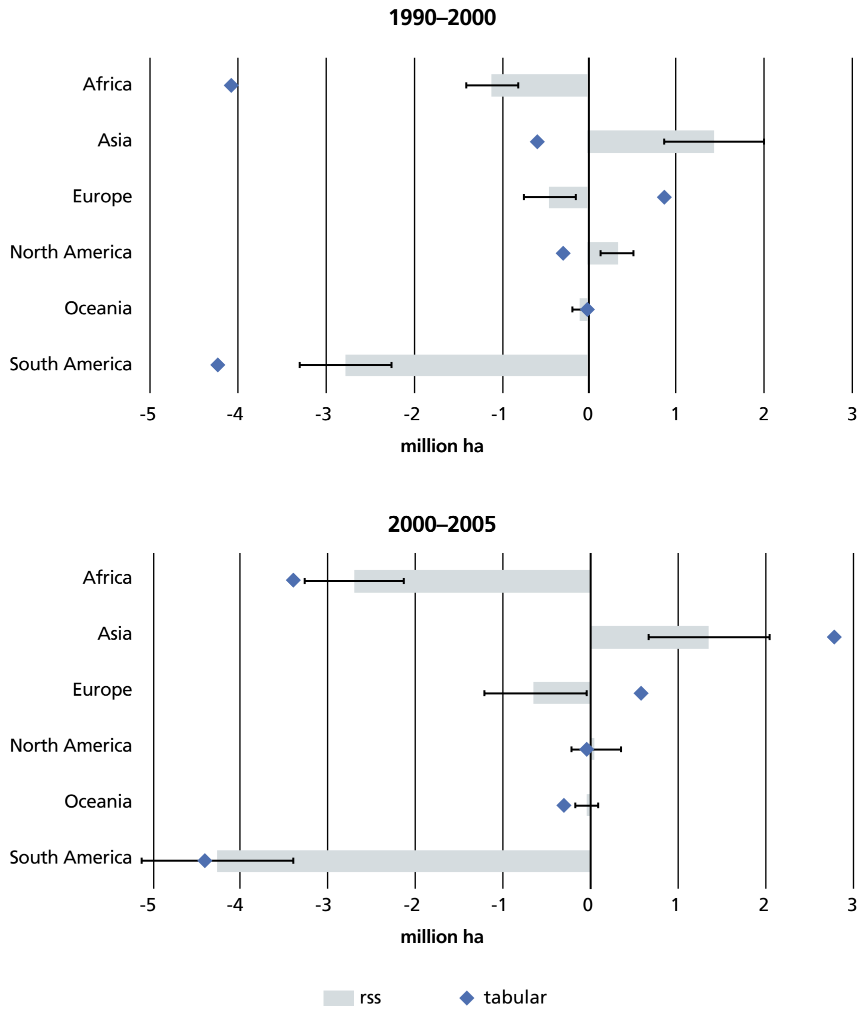
Differences in net forest area change

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.