Determination of tropical deforestation rates and related carbon losses from 1990 to 2010

FRÉDÉRIC ACHARD¹, RENÉ BEUCHLE¹, PHILIPPE MAYAUX¹, HANS-JÜRGEN STIBIG¹, CATHERINE BODART¹:², ANDREAS BRINK¹, SILVIA CARBONI³, BAUDOUIN DESCLEE¹, FRANÇOIS DONNAY³, HUGH D. EVA¹, ANDREA LUPI⁴, RASTISŁAV RASI¹:⁵, ROMAN SELIGER³ and DARIO SIMONETTI⁴

¹Institute for Environment and Sustainability, Joint Research Centre of the European Commission, TP 440, Ispra, VA 21027, Italy, ²Food and Agriculture Organisation of the United Nations, Rome, Italy, ³Joint Research Centre of the European Commission, Engineering SpA, Ispra, Italy, ⁴Arcadia SIT, Joint Research Centre of the European Commission, Ispra, Italy, ⁵National Forest Centre, Forest Research Institute, Zvolen 96092, Slovak Republic

Abstract

We estimate changes in forest cover (deforestation and forest regrowth) in the tropics for the two last decades (1990–2000 and 2000–2010) based on a sample of 4000 units of 10 × 10 km size. Forest cover is interpreted from satellite imagery at 30 × 30 m resolution. Forest cover changes are then combined with pan-tropical biomass maps to estimate carbon losses. We show that there was a gross loss of tropical forests of 8.0 million ha yr⁻¹ in the 1990s and 7.6 million ha yr⁻¹ in the 2000s (0.49% annual rate), with no statistically significant difference. Humid forests account for 64% of the total forest cover in 2010 and 54% of the net forest loss during second study decade. Losses of forest cover and Other Wooded Land (OWL) cover result in estimates of carbon losses which are similar for 1990s and 2000s at 887 MtC yr⁻¹ (range: 646–1238) and 880 MtC yr⁻¹ (range: 602–1237) respectively, with humid regions contributing two-thirds. The estimates of forest area changes have small statistical standard errors due to large sample size. We also reduce uncertainties of previous estimates of carbon losses and removals. Our estimates of forest area change are significantly lower as compared to national survey data. We reconcile recent low estimates of carbon emissions from tropical deforestation for early 2000s and show that carbon loss rates did not change between the two last decades. Carbon losses from deforestation represent circa 10% of Carbon emissions from fossil fuel combustion and cement production during the last decade (2000–2010). Our estimates of annual removals of carbon from forest regrowth at 115 MtC yr⁻¹ (range: 61–168) and 97 MtC yr⁻¹ (53–141) for the 1990s and 2000s respectively are five to fifteen times lower than earlier published estimates.

Keywords: carbon emissions from tropical deforestation, carbon removals from tropical forest regrowth, climate change impacts, forest cover changes in tropics for the 1990s and the 2000s, spatial explicit use of pan tropical biomass maps combined with detailed deforestation maps

Received 8 November 2013; revised version received 3 March 2014 and accepted 1 April 2014

Introduction

Since the early 1990s, the European Commission’s Joint Research Centre (JRC) monitors the tropical forests with remote sensing (TREES Project) with the goal of reducing uncertainties in measuring forest change and related carbon emissions (Achard et al., 2002, 2004). In the third phase of the project, launched in 2007, the extent and changes of tropical forests areas are assessed for the period 1990–2000–2010. This is done from a systematic sample of observation units covered with Landsat-TM type satellite imagery (30 × 30 m resolution) that was acquired for the three reference years (around years 1990, 2000, and 2010, respectively). The use of satellite imagery is the only feasible way to consistently monitor forest cover change over very large regions given the cost of field inventory in the tropics and the lack of comparable historical national forest inventory data.

In our study, we use a systematic sample of 10 × 10 km size units located at each full Latitude and Longitude confluence point (Mayaux et al., 2005; Beuchle et al., 2011). This sample contains 4016 sample sites covering (aside from Mexico) all tropical countries (Fig. 1) and circa 1% of the total tropical zone. The study is a continuation of an initial exercise carried out in co-ordination with the United Nations Food and Agricultural Organization (FAO) for their Global Forest Resource Assessment 2010 (FRA-2010) Remote Sensing Survey (RSS), which focused on the assessment of forest land-use change between 1990 and 2005 (Eva et al.,...
2012; FAO, JRC, 2012; Bodart et al., 2013; Ernst et al., 2013). Unlike global country surveys which provide global tables with national data (FAO, 2010), this remote sensing survey is aimed at providing a sample of spatially explicit data distributed across the whole tropical belt.

The method allows producing statistically valid estimates of forest cover changes at regional or continental scale (Eva et al., 2012; Mayaux et al., 2013; Stibig et al., 2014). Careful attention is given to the estimates of losses of carbon from forest cover changes at regional levels: when combined with maps of biomass available over the tropics (Baccini et al., 2012; Saatchi et al., 2011), our land-cover change maps lead to spatially explicit information on tropical carbon emissions and removals. As these two tropical biomass maps are single-date type (circa 2007 and 2000 respectively), have coarse resolution (500 × 500 m or 1 × 1 km respectively), and high uncertainties at pixel level (ca. 40%), we used average biomass density values within our 10 × 10 km size units.

Most of the net flux of carbon into the atmosphere due to land-cover changes is attributable to deforestation in the tropics, with a smaller fraction attributable to forest degradation (Houghton et al., 2012). Forest degradation in the tropics is considered to account for more of the gross emissions than deforestation, but these emissions are largely compensated by the gross annual sink of regrowth in logged forests or fallows of shifting cultivation, whilst a smaller sink is attributable to reforestation (increase in forest area) (Baccini et al., 2012; Houghton et al., 2012; Pan et al., 2011). Forest degradation is a key process for the UNFCCC REDD+ mechanism (Reduction of Emissions from Deforestation and forest Degradation). Assessing through remote sensing data areas within tropical forests where forest

Fig. 1 Proportions of forest cover within all sample sites over the tree continents for year 2010.
Materials and methods

Sampling design

In our previous tropical surveys for the 1990s (Achard et al., 2002), we implemented a sophisticated stratification that improved the statistical efficiency and increased the accuracy of the estimates; however, the irregular layout of these sampling designs has been demonstrated to be less credible outside the scientific community and less adaptable to changes in study size and in time (Eva et al., 2010). This experience led us to select a nonstratified global systematic sample design. We selected a systematic sampling grid with sample units centered at each degree confluence (e.g., 12° South 58° West). The statistical loss of accuracy of such systematic sample can be compensated by (i) variance reduction by using sample sites of small size and (ii) potential improvements with regression estimators such as local variance estimator (Stehman, 2005). The adopted systematic sampling is easy to intensify and to better link with national surveys (see: www.fao.org/forestry/ nfm). Our sample grid provides 4016 sample units uniformly distributed across the entire study area (all tropical countries except Mexico). Each unit has a size of 10 km by 10 km for which Landsat satellite data with medium spatial ground resolution (30 × 30 m) were acquired as close as possible to the reference years of 1990, 2000, and 2010.

Acquisition of Satellite imagery

While for the first two ‘reference years’ of the study (1990 and 2000), the coverage by TM imagery from Landsat 4, Landsat 5 (1990) and by ETM+ imagery from Landsat 7 (2000) is almost complete (Beuchle et al., 2011), Landsat imagery for the 2010 reference year suffers from the failure of Landsat 7’s scan line correction in 2003. For example, for South America and for the 2010 epoch (mainly covered by Landsat 5 data), 13% of the sample sites are covered by alternative imagery from other fine or medium resolution optical sensors (in particular for regions with persistent cloud cover) with only 1% of the 1230 sample sites missing due to the lack of cloud-free images. Alternative satellite data for year 2010 were received for South America and Southeast Asia, namely from the RapidEye, AVNIR-2, Kompsat and Deimos-1 sensors. Alternative satellite data were also used for Africa, in particular over the Congo Basin from the Deimos-1, UK-DMC2, and SPOT-4 & 5 satellites. The intermediate epoch 2005 (which was used for the FAO FRA-2010 Remote Sensing Survey) is not reported here because (i) the analysis is comparing the two most recent decades and (ii) there is a significant number of missing sample units (due to missing imagery) for epoch 2005 (350 in total).

Preprocessing of satellite imagery

All satellite images were preprocessed, including geo-location correction, conversion into top-of-atmosphere reflectance, atmospheric correction (haze-correction and masking of cloud and cloud shadow) and normalization by dark-object subtraction on basis of dense evergreen humid forest areas (Bodart et al., 2011). The segmentation process targeted a Minimum Mapping Unit (MMU) of 5 ha, tolerating within each sample unit a maximum number of 5% of smaller polygons resulting from the segmentation procedure. Polygons smaller than 3 ha were merged with their neighbors (Rasi et al., 2011). An automatic process of object-based change detection and classification was designed for Landsat images (Rasi et al., 2013) and the process adapted for alternative imagery (Desclée et al., 2013).

Thematic legend for the analysis of satellite imagery

The FAO definition of ‘forest’ includes all areas of at least 0.5 ha size with tree cover (canopy) density greater than 10% and tree height greater than 5 m (FAO, 2010). However, these thresholds cannot be ‘measured’ from Landsat satellite imagery with high accuracy. A more feasible assessment is that the canopy density be greater than 30% (FAO, JRC, 2012). The 7th Conference of the Parties of the United Nations Framework Convention on Climate Change (UNFCCC) adopted (the ‘Marakesh accords’) a forest definition with certain flexibility: ‘Forest’ is a minimum area of land of 0.05–1.0 ha with tree crown cover of more than 10–30%. To date for UNFCC reporting, most countries are defining forests with a minimum crown cover of 30%. Within our study, we used a MMU of 1 ha as an intermediate step in image processing and a 3 ha MMU for producing the final mapping results. We used five land-cover classes at 3 ha level: (i) areas with portion of tree cover over 70% within the unit (‘Tree Cover’); (ii) those with 30–70% portion (‘Tree Cover Mosaic’); (iii) all other woody vegetation (height <5 m), including shrubs and forest regrowths (‘Other Wooded Land’); (iv) Water; and (v) ‘Other Land Cover’. The satellite data from each reference year (1990, 2000, and 2010) are processed and classified into the five land-cover classes using a supervised classifier (Rasi et al., 2011, 2013).

After visual quality control by national experts, we produce from the resulting three-date interpretations the matrices of the class transitions for the two periods 1990–2000 and 2000–2010. These matrices allow calculating gross and net rates of land-cover conversions. We may only miss the processes of reclearing of shrubland within a 10-year period. Forest areas are then calculated as 100% areas of the ‘Tree Cover’ class plus 50% areas of the ‘Tree Cover Mosaic’ class.
Our study does not fully assess forest degradation because selective logging and moderate forest fragmentation occurring below the defined MMU are usually not reflected by a change in the land-cover class. However, degradation is generally an initial phase in the conversion of forests (Numata et al., 2010).

**Statistical extrapolation to continental or tropical levels**

It was not possible to acquire the satellite images at the exact reference date (Beuchle et al., 2011). Each sample site’s area estimate was therefore linearly adjusted to the baseline dates of 30th June 1990, 2000, and 2010; this was done by assuming that the land-cover change rates are constant during the given period. Cloudy areas were considered as an unbiased loss of data, and assumed to have the same proportions of land cover as noncloudy areas within the same site. This is achieved by converting the land-cover change matrices 1990–2000 and 2000–2010 to area proportions relative to the total cloud-free land area of the sample units. For the missing sample units (4, 39, and 3 for 1990–2000 and 3, 39, and 3 for 2000–2010, for South America, Africa and Southeast Asia, respectively, from totals of 1230, 2045, and 741 sample units, respectively), we used a local average from surrounding sample sites as surrogate results. The following weights ($\delta_{ij}$) were applied for the local average of missing sites:

$$\delta_{ij} = 1/d(j, f) = 1/(\text{dif(lat)})^4 + (\text{dif(long)})^4$$

(1)

where $d(j, f)$ is the distance between two sites.

For the statistical estimation phase, the sample units are weighted in relation to their statistical probability of selection. Indeed, the sampling frame, although systematic, does not give equal probability to all sample units because the distance between sample units along a parallel is not the same as the distance along a meridian. All sample units are given a weight, equal to the cosine of the latitude to account for this unequal probability. The impact of these weights is moderate in tropical areas. The sample units that contain a proportion of sea compensate for unselected sample sites that contain a proportion of land (when the centre of the site is located in the sea) because they were considered as full sites.

The proportions of land-cover changes were then extrapolated to the study area using the Horvitz-Thompson Direct Expansion Estimator (Särndal et al., 1992). The estimator for each land-cover class transition is the mean proportion of that change per sample unit, given by Eqn 2:

$$\bar{y}_i = \frac{1}{m} \sum_{j=1}^{m} w_i y_{ic}$$

(2)

where $y_{ic}$ is the proportion of land-cover change for a particular class transition in the $i$th sample unit. The weight of the sample unit is $w_i$ and $m$ is the sum of the sample weights.

The usual variance estimation of the mean is known to have a positive bias (Stehman et al., 2011). Alternative estimators based on a local estimation of the variance have been shown to reduce the bias. We use an estimator of the standard error based on local variance estimation:

$$S^2 = (1-f) \frac{\sum_j w_j \delta_j (y_j-y_i)^2}{2 \sum_j w_j \delta_j}$$

(3)

where $f$ is the sampling rate, the weight $w_j$ is an average of the weights $w_i$ and $w_j$, and $\delta_j$ is a decreasing function of the distance between $j$ and $f$ (note that if we choose $\delta_j = 0$, we have the usual variance estimator). The standard error (SE) is then calculated as:

$$\text{SE} = \frac{s}{\sqrt{n}}$$

(4)

where $n$ is the total number of available sample sites (i.e. not accounting for the missing sites even if they are replaced by a local average).

**Accuracy assessment of the estimates of forest cover changes**

The observations (source datasets) that are used to produce our results are derived from satellite interpretations. These surrogates to ground observations may be subject to the uncertainty (bias) (Foody, 2010), but we do not address such errors here. The use of such surrogate data for assessing area change is inevitable in many areas of the tropics where no ground observations exist and where large areas of inaccessible forests can only be monitored at affordable costs by the exploitation of satellite data. However, we performed an independent assessment over 1185, 1552, and 830 points (total: 3567 points) distributed systematically within a random subsample of 240, 338, and 166 sample units in South America, Africa, and Southeast Asia, respectively (a central point plus four points in the corners taken in each sample unit). In addition, we selected from a 9 x 9 systematic grid (81 points taken at 1 km distance in each sample unit) all points identified as change in land cover during the period 1990–2000, resulting in 1663, 1194, and 1425 points (total: 4282), respectively, for the three subregions. The corresponding polygons were carefully visually reinterpreted by independent experts using ancillary information when available (e.g., imagery from Google Earth© considering the date of imagery). This allows assessing the ‘consistency’ of the results of the interpretation.

To complement to this consistency assessment, we also compared our results to the INPE interpretations for period 1990–2000 (INPE, 2013) for a random selection of 34 sample units among the 411 sample units falling in the Brazilian Legal Amazon (Eva et al., 2012).

**Combining forest cover change maps with pan-tropical biomass maps to estimate carbon fluxes**

Biomass data for tree cover and other wooded land are spatially associated with each sample site, so that the per-site carbon emissions (and removals) can be calculated. We use three datasets of spatially explicit biomass information: the FAO ecozone map (FAO, 2012) combined with IPCC values (IPCC, 2006), and Baccini et al. (2012) and Saatchi et al. (2011) pan-tropical biomass maps.
The FAO ecozone map is combined with Above Ground Biomass (AGB) levels for the major tropical ecosystems (evergreen rainforests, rainforests with seasonal behavior, moist deciduous forests, dry forests, mountain ecosystems, shrubland, subtropical humid forests, grasslands, desert) derived from IPCC ‘Tier 1’ data, complemented by a regional dataset of aboveground biomass for Amazon basin (Malhi et al., 2006). We used the IPCC ratio of belowground biomass to aboveground biomass for conversion into total biomass (from 0.37 to 0.24 depending on the ecosystem).

The pan-tropical maps of forest carbon density at 500 m (Baccini et al., 2012) and 1 km resolution (Saatchi et al., 2011) are derived from a combination of field inventory plots, Geoscience Laser Altimeter System (GLAS) data points acquired from the ICESat Satellite and products of the moderate resolution imaging spectro-radiometer (MODIS). However, while Baccini et al. (2012) only estimated the AGB and aboveground carbon portion, Saatchi et al. (2011) also took into account the belowground biomass and carbon content. Both datasets show uncertainty information at continental level, and Saatchi’s map provides uncertainty information for each pixel location. For the dataset of Baccini et al. (2012), we derive a map of the total carbon (above- and belowground) by applying the following equation used by Saatchi et al. (2011):

\[
\text{Total Biomass} = \text{AGB} + 0.489 \times \text{AGB}^{0.89}.
\]

From these three pan-tropical biomass datasets, we derive five values of total biomass for the three wooded classes (‘Tree Cover’, ‘Tree Cover Mosaic’, and ‘Other Wooded Land’) for each sample site: (i) IPCC/Ecozone average; (ii) Baccini average; (iii) ‘Saatchi average’; (iv) ‘Saatchi maximum’; and (v) ‘Saatchi minimum’. The biomass values for (i), (ii), and (iii) are derived as follows: for each of the three available biomass maps, we consider the average biomass values of the pixels falling completely within the polygons labeled either as ‘Tree Cover’ or ‘Other Wooded Land’ in each single sample unit. As the polygons labeled as ‘Tree Cover Mosaic’ usually contain fragmented land cover and, moreover, are relative small leading to a limited number of 500 m or 1 km resolution pixels, we consider for this class the average biomass value of the ‘Tree Cover’ and ‘Other Wooded Land’ classes in each sample unit.

Baccini et al. (2012) provide relative standard deviation of errors on a continental basis at 6.6%, 3.6%, and 3.2% for tropical Africa, tropical America and tropical Asia, respectively, Saatchi et al. (2011) provide relative uncertainty ranges for different scales: from ±6% to ±53% at pixel (1 km resolution), ±5% at project (~10,000 ha), and ±1% at national levels. For a sensitivity analysis of uncertainties, we use the uncertainty values reported in Saatchi’s dataset at pixel level. For the ‘Tree Cover’ and ‘Other Wooded Land’ classes, we consider the average of the uncertainty values of the Saatchi pixels falling within the polygons labeled as one of these two classes for each single sample unit. These uncertainty averages are then used to produce ‘Saatchi maximum’ (‘Saatchi average’ plus uncertainty average) and ‘Saatchi minimum’ (‘Saatchi average’ minus uncertainty average) for each of these two classes.

It should be noted that the average of the uncertainty values is around 60 t ha\(^{-1}\) for all sample units with small variance between sample units.

We estimated total carbon as 50% of total biomass. We do not account for losses of carbon in soils.

In a previous study (Achard et al., 2004), the annual carbon gross emissions for the study area were calculated as the committed emissions over a 10 year period arising from 1 year of forest and woodland clearance. We aimed at taking into account the land-cover dynamics following deforestation, including the decay of product and slash pools (Ramankutty et al., 2007). These annual emissions accounted for 69% of the total initial carbon stocks. In this study, we consider only the maximum potential loss of carbon which can be emitted in the atmosphere over a long time period, corresponding to 100% of the total initial carbon stocks. In other words, we consider here that emissions would occur fully at time of clearing and referred to as committed emissions.

**Carbon removals from forest regeneration**

We also consider the carbon removals from forest regeneration by combining our estimates of forest regrowth areas (nonforested areas changing to forest areas) with annual carbon gains in secondary vegetation derived from the biomass datasets. We produce three estimates of biomass increment on tropical regrowth forests for each sample unit from the three datasets of spatially explicit information on biomass. From the IPCC/ecozone biomass map, we derive a first value of biomass increment by considering that forest regrowth will recover their total biomass (i.e. biomass of the ‘Tree Cover’ class) in 25 years, as supported by IPCC values for young regrowth (~20 years) of tropical rain forest with a continental range of 22-31 years (IPCC, 2006). We produce two other values of biomass increment from the Baccini and Saatchi maps by considering (i) the minimum of the two biomass values (Baccini and Saatchi) for the tree cover class with a 30 year period for full regrowth and (ii) the maximum of the two biomass values (Baccini and Saatchi) for the tree cover class with a 20 year period for full regrowth. These ‘minimum’ and ‘maximum’ biomass increment values will allow assessing the sensitivity of biomass increment values on estimates of carbon removals.

**Results**

**Changes in forest and other wooded land cover**

We estimate that for the year 1990, there were 1635 million ha of tropical forest and 964 million ha of other wooded land (standard errors are reported in Table 1). By 2010, the forest area has fallen to 1514 million ha (Fig. 1) with an overall net loss over the two decades of 56.9, 30.9, and 32.9 million ha in ‘South and Central
Table 1  Tropical ‘Forest’ and Other Wooded Land (OWL) cover for years 1990, 2000, and 2010, and annual changes during decades 1990–2000 and 2000–2010. The ‘Dry’ vs. ‘Humid’ domains are based on FAO ecological zones for South America and Africa. Area estimates are in million ha. Area change estimates are in million ha yr$^{-1}$. SE represent standard errors due to use of a sample.

| Central & South America | Tropical Africa | Southeast Asia | Tropics |
|-------------------------|-----------------|----------------|---------|
| **Dry** | **Humid** | **Dry** | **Humid** | **Dry** & **Insular** | **Dry** | **Humid** | **Total** |
| **Area** | **SE** | **Area** | **SE** | **Area** | **SE** | **Area** | **SE** | **Area** | **SE** | **Area** | **SE** |
| Total Area | 572 | 903 | 2081 | 333 | 555 | 303 | 3207 | 1539 | 4746 |
| Forest 1990 | 163.3 | 5.0 | 636.9 | 7.7 | 131.2 | 5.8 | 187.9 | 4.8 | 592 | 11.3 | 1 043 | 10.3 | 1635 | 15.3 |
| Forest 2000 | 153.4 | 4.8 | 618.3 | 8.0 | 128.5 | 5.7 | 172.8 | 5.0 | 571 | 11.1 | 1 004 | 10.6 | 1574 | 15.4 |
| Forest 2010 | 144.2 | 4.7 | 599.1 | 8.2 | 122.7 | 5.6 | 163.5 | 5.1 | 542 | 10.8 | 972 | 10.7 | 1514 | 15.2 |
| OWL 1990 | 128.7 | 4.6 | 401.2 | 2.1 | 631.2 | 11.1 | 52.4 | 3.5 | 60.1 | 3.6 | 571 | 11.1 | 1 043 | 10.3 | 1635 | 15.3 |
| OWL 2000 | 125.1 | 4.5 | 42.2 | 2.0 | 627.3 | 11.1 | 56.6 | 3.6 | 62.9 | 3.2 | 60.1 | 3.6 | 815 | 12.4 | 159 | 5.5 | 974 | 13.5 |
| OWL 2010 | 121.1 | 4.5 | 44.4 | 2.1 | 622.6 | 10.9 | 57.1 | 3.7 | 64.4 | 3.2 | 65.8 | 3.8 | 808 | 12.2 | 167 | 5.7 | 975 | 13.5 |
| Annual gross deforestation | | | | | | | | | |
| 1990–2000 | 1.46 | 0.12 | 2.38 | 0.18 | 1.33 | 0.10 | 0.70 | 0.09 | 0.41 | 0.07 | 1.70 | 0.19 | 3.20 | 0.17 | 4.77 | 0.17 | 7.97 | 0.33 |
| 2000–2010 | 1.42 | 0.14 | 2.49 | 0.20 | 1.47 | 0.11 | 0.36 | 0.05 | 0.66 | 0.10 | 1.22 | 0.16 | 3.55 | 0.21 | 4.07 | 0.26 | 7.62 | 0.33 |
| Annual forest regrowth | | | | | | | | | |
| 1990–2000 | 0.47 | 0.06 | 0.52 | 0.04 | 0.49 | 0.06 | 0.11 | 0.02 | 0.14 | 0.04 | 0.19 | 0.03 | 1.11 | 0.09 | 0.81 | 0.05 | 1.92 | 0.11 |
| 2000–2010 | 0.50 | 0.07 | 0.57 | 0.04 | 0.11 | 0.02 | 0.02 | 0.01 | 0.09 | 0.01 | 0.26 | 0.07 | 0.70 | 0.07 | 0.85 | 0.08 | 1.55 | 0.11 |
| Annual net deforestation | | | | | | | | | |
| 1990–2000 | 0.99 | 0.14 | 1.86 | 0.21 | 0.83 | 0.17 | 0.59 | 0.13 | 0.27 | 0.08 | 1.51 | 0.25 | 2.09 | 0.24 | 3.96 | 0.36 | 6.05 | 0.43 |
| 2000–2010 | 0.92 | 0.16 | 1.92 | 0.23 | 1.36 | 0.19 | 0.29 | 0.05 | 0.48 | 0.13 | 0.96 | 0.22 | 2.76 | 0.28 | 3.17 | 0.32 | 5.93 | 0.43 |
| Annual gross loss OWL | | | | | | | | | |
| 1990–2000 | 1.48 | 0.09 | 0.45 | 0.04 | 1.79 | 0.11 | 0.19 | 0.03 | 0.26 | 0.04 | 0.52 | 0.08 | 3.52 | 0.15 | 1.16 | 0.09 | 4.69 | 0.18 |
| 2000–2010 | 1.44 | 0.10 | 0.66 | 0.07 | 1.37 | 0.08 | 0.15 | 0.03 | 0.37 | 0.05 | 0.50 | 0.07 | 3.17 | 0.14 | 1.31 | 0.10 | 4.48 | 0.17 |
| Annual net loss OWL | | | | | | | | | |
| 1990–2000 | 0.36 | 0.12 | −0.21 | 0.04 | 0.39 | 0.13 | 0.53 | 0.16 | −0.28 | 0.07 | −0.86 | 0.17 | 0.47 | 0.19 | −0.54 | 0.24 | −0.07 | 0.30 |
| 2000–2010 | 0.40 | 0.11 | −0.21 | 0.10 | 0.47 | 0.09 | −0.05 | 0.03 | −0.13 | 0.07 | −0.63 | 0.16 | 0.73 | 0.16 | −0.89 | 0.19 | −0.16 | 0.24 |
America and the Caribbean’, ‘sub-Saharan Africa’ and ‘South and Southeast Asia’, respectively (referred as South America, Africa and Southeast Asia later in the text). Other wooded land increased in that period to 975 million ha, mainly due to the increase of 18.6 million ha in Southeast Asia (Table 1). In 2010, humid tropical forests accounted for ca. 64% of the tropical forest cover i.e. 972 million ha from a total of 1514 million ha, with the following regional distribution: 599 million ha in South America, 210 million ha in Africa, and 163 million ha in Southeast Asia.

At global level, the gross loss of tropical forests was 8.0 million ha yr\(^{-1}\) during 1990s (0.497% annually) with a slight decrease of 7.6 million ha yr\(^{-1}\) during the 2000s (0.494% annually), mainly due to reduced deforestation rates in the humid forests of Africa and Southeast Asia (from 0.70 to 0.36 million ha yr\(^{-1}\) and from 1.70 to 1.22 million ha yr\(^{-1}\), respectively) (Fig. 2).

Large nonforest areas were also reoccupied by forests, reaching 1.9 million ha yr\(^{-1}\) in the 1990s and 1.6 million ha yr\(^{-1}\) in the 2000s, where the humd part contributed 42% and 55%, respectively. South America accounts for 1.0 million ha yr\(^{-1}\) in the 1990s and 1.1 million ha yr\(^{-1}\) in 2000s.

The resulting global net losses of tropical forests were 6.1 million ha yr\(^{-1}\) during the 1990s (0.377% annually) and 5.9 million ha yr\(^{-1}\) during the 2000s (0.384% annually), thus showing no significant difference for the two

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**Fig. 2** Losses of forest cover and other wooded land for all sample sites over the tree continents and the two periods: 1990–2000 and 2000–2010. Gross loss of forest cover appears in orange circles when gross loss from other woodland losses appears in yellow circles. Range is 0–100% loss over one decade.

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periods. The contribution of humid forests to the net forest loss decreased from 65% to 54% from the 1990s to the 2000s (from 4.0 million ha yr\(^{-1}\) to 3.2 million ha yr\(^{-1}\), respectively).

Carbon losses and removals from changes in forest and other wooded land cover

Our estimate of annual carbon gross loss from changes in forest and other wooded land cover are 887 MtC yr\(^{-1}\) (range: 646–1238) and 880 MtC yr\(^{-1}\) (602–1237) for the 1990s and 2000s, respectively (Table 2), the tropical humid regions contributing 66.7% and 62.2%, respectively (Fig. 3). Carbon losses are very similar over the two last decades when IPCC (2013) reports that ‘it is more likely than not that net CO\(_2\) emissions from land-use change decreased during 2000–2011 compared to 1990–1999’. Carbon losses from deforestation of the last decade (2000–2010) represent circa 10% of Carbon emissions from fossil fuel combustion and cement production at 8.3 ± 0.7 PgC yr\(^{-1}\) (IPCC, 2013).

Taking our estimate of 10 years of regrowth as an estimate of accumulated forest regrowth areas at the beginning of each decade to provide an estimate of annual carbon gains in forest regrowth, we obtain potential annual removals (sinks) of carbon from forest regrowth at 115 MtC yr\(^{-1}\) (range: 61–168) and 97 MtC yr\(^{-1}\) (53–141) for the 1990s and 2000s, respectively (Table 3).

Uncertainties of the estimates

The estimates of forest area changes (gross loss, gross gain, net loss) have small statistical standard errors due to large sample size: from 4% to 10% at global level and from 11% to 19% as average at regional level. A dedicated accuracy assessment was carried out for the land-cover maps of the period 1990–2000. The overall agreements between our results and the reinterpretations considered as reference information are: 92.9% for the forest labels (94.5%, 94.0%, and 88.7% for South America, Africa and Southeast Asia, respectively) and 85.5% for the
Table 2  Annual Carbon losses from gross loss of tropical forest cover and other wooded land for periods 1990–2000 and 2000–2010 (values in 10^6 tC yr^{-1})

|                          | Central & South America | Africa | Southeast Asia | Global |
|--------------------------|-------------------------|--------|----------------|--------|
| **Period 1990–2000**     |                         |        |                |        |
| Our study with Ecozone/IPCC | 670.8                  | 236.8  | 420.5          | 1328   |
| Our study with Maximum Saatchi | 622.6                  | 265.8  | 349.5          | 1238   |
| Our study with Average Baccini/Saatchi | 443.4                  | 178.7  | 265.2          | 887    |
| Our study with Minimum Saatchi | 306.5                  | 102.1  | 237.1          | 646    |
| FAO (2010)               | 357.7                   | 264.2  | 201.7          | 824    |
| **Period 2000–2010**     |                         |        |                |        |
| Our study with Ecozone/IPCC | 677.1                  | 200.8  | 360.7          | 1239   |
| Our study with Maximum Saatchi | 649.7                  | 220.7  | 367.1          | 1237   |
| Our study with Average Baccini/Saatchi | 464.8                  | 147.7  | 267.1          | 880    |
| Our study with Minimum Saatchi | 322.6                  | 43.5   | 235.5          | 602    |
| FAO (2010)               | 340.1                   | 241.3  | 297.7          | 879    |
| Baccini et al. (2012) for period 2000–2005 | 470                   | 230    | 110            | 810    |
| Harris et al. (2012a,b) for period 2000–2005 | 440                   | 110    | 260            | 810    |

Discussion

Comparison of results of changes in forest and other wooded land cover with other studies

Our estimates of forest cover for year 2010 (1514 million ha) and net forest cover loss for 1990s and 2000s (6.05 million ha yr^{-1} and 5.93 million ha yr^{-1}) are respectively 18%, 44%, and 28% lower than the figures from the FAO country survey for the same set of countries with 1833 million ha of forest extent for year 2010, 10.9 million ha yr^{-1} and 8.5 million ha yr^{-1} of net forest area loss for 1990s and 2000s (FAO, 2010). Conversely, our estimate of Other Wooded Land for year 2010 at 975 million ha is much higher than the FAO estimate of ‘other wooded land’ at 526 million ha. The discrepancies between the FAO country survey study and our remote sensing surveys can be explained by the difference in the definition of forest (FAO uses a forest land-use definition when our study uses a forest cover definition) and the use of national statistics for the FAO country survey with their known limitations in terms of data quality and consistency between countries (Grainger, 2008). For the woodlands, the discrepancy can be partly explained by the fact that our class ‘Other Wooded Land’ may include areas of low density tree cover, which can be considered as forested land by FAO when the tree cover portion is over 10%. On Landsat type of satellite imagery, it is difficult to precisely differentiate between tree cover densities in the range of 0–30%, with a tendency to assign such areas as OWL due to their spectral similarity with pure OWL areas. This class is the most prone to inaccuracies in both surveys because of the large uncertainties in national forest information and the limitations of satellite image interpretation.

Our estimates can also be compared to results from a recent global study of forest cover changes derived...
from Landsat imagery over the period 2000–2012 (Hansen et al., 2013). This study uses four ‘Tree Cover’ classes: ‘<25% TC’, ‘26–50% TC’, ‘51–76% TC’, and ‘76–100% TC’. Forest cover loss is reported as the sum of losses from the four classes while forest cover gain is defined as change from nonforest to more than 50% tree cover. Forest cover is not explicitly defined in this study. The four classes together correspond to the total land area. If we consider only the 76–100% TC class as forests, it would lead to a good correspondence with our estimates of forest cover for South America and Southeast Asia (770 and 319 million ha, respectively), but to a much lower estimate of forest cover for Africa (212 million ha). By considering the two classes with more than 50% tree cover as forest, we obtain a good agreement with our global estimates of forest cover and gross forest loss (4% and 6% relative difference, respectively), but continental estimates show large discrepancies – up to 22% (Table 4). Values for class ‘26–50% TC’ are also much lower than either our estimates or FAO’s values for OWL (Table 4).

These discrepancies between the Hansen et al. (2013) study and our remote sensing surveys can be explained by differences in the definitions of forest and in the approaches which are used to analyze the satellite imagery. A large part of these
discrepancies might be explained by the difficulty in correctly extracting tree cover percentages for dry open forest types (e.g., Miombo in Africa). This is especially true for low tree cover densities (<30%), as well as shrub cover (OWL).

**Comparison of results of carbon losses and removals with other studies**

Our estimates of carbon losses and removals can be compared to published estimates of carbon emissions for Brazil. From the 707 sample units of our study which cover the Brazilian territory, our estimates of annual CO$_2$ emissions for the 1990s are 1091 MtCO$_2$ yr$^{-1}$ ($\pm 424$ MtCO$_2$ yr$^{-1}$ when considering min–max errors from Saatchi map) as potential long-term emissions. For the 2000s, we estimate 1137 MtCO$_2$ yr$^{-1}$ ($\pm 405$ MtCO$_2$ yr$^{-1}$). These estimates can be compared to the figures of annual net anthropogenic CO$_2$ emissions from the Land-use Change and Forestry sector (Second National Communication of Brazil to the UNFCCC: Brazil, 2010) which give 761, 821, 1249, and 1251 MtCO$_2$ yr$^{-1}$ for the accounting years 1990, 1994, 2000, and 2005, respectively. These net figures include four different components: sources from ‘Forest and Grassland conversions’ and from ‘Emissions and Removals from Soils’ and sinks from ‘Changes in Forest and Other Woody Biomass Stocks’ and from ‘Abandonment of Managed Land’. In the first Brazilian communication (Cerri et al., 2009), sources from soils represent an average of 7% of the sources from land conversions when the sinks compensate for around 25% of the sources. This translates into national figures of sources from forest conversions at around 1100 MtCO$_2$ yr$^{-1}$ for the 1990s and 1400 MtCO$_2$ yr$^{-1}$ for the early 2000s during which rates of deforestation in Brazilian Amazon where much higher than for the late 2000s. The resulting official estimate of annual CO$_2$ emissions from forest conversions for the 1990s (1100 MtCO$_2$ yr$^{-1}$) is in very good agreement with our estimate of annual CO$_2$ emissions at 1091 MtCO$_2$ yr$^{-1}$.

Our estimate of carbon removals from forest regrowth for Brazil is 124 MtCO$_2$ yr$^{-1}$ for the 1990s and 149 MtCO$_2$ yr$^{-1}$ for the 2000s. By considering that in

**Fig. 3 Continued**

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the official Brazilian figures of net emissions carbon sinks compensate for around 25% of the carbon sources, this would lead to a national figure of sinks from the Land-use Change and Forestry sector at 235 Mt CO$_2$ yr$^{-1}$ (average for years 1990, 1994, 2000, and 2005). This figure is respectively 48% and 38% higher than our estimates, but it includes sinks from ‘Changes in Forest and Other Woody Biomass Stocks’ and from ‘Abandonment of Managed Land’ (the later corresponding to forest regrowths). Unfortunately, there is no information available from Cerri et al. (2009) nor from the second National Communication of Brazil to the UNFCCC (Brazil, 2010) on the share between these two components.

We also compare our estimates of carbon losses during period 2000–2010 to two recent estimates of carbon emissions from tropical deforestation by Wood Hole Research Cente (WHRC) (Baccini et al., 2012) and WinRock International (Harris et al., 2012a,b) that, upon first review, seemed to differ widely. These studies cover only the first half of the 2000s, i.e. from year 2000 to year 2005 and use rates of deforestation which are different than ours (higher for South America and Africa and lower for Southeast Asia –Table 5). Our average continental estimates fall in between the estimates from the WHRC and WinRock studies for South America and Africa and at the level of the highest estimate (from WinRock) for Southeast Asia (Table 2). Our average estimates correspond well to FAO figures of forest biomass loss over the two decades (FAO, 2010). However, the FAO figures include also losses from forest degradation which are only partially considered in

|                | Central + South America | Africa | Southeast Asia | Global |
|----------------|-------------------------|--------|----------------|--------|
|                | Estimate | Range | Estimate | Range | Estimate | Range |
| 1990–2000      | Our study with Average Baccini/Saatchi | 57.7 | 27.1 | 30.4 | 15.1 | 26.4 | 11.3 | 115 | 54 |
|                | Our study with Ecozone map | 59.2 | 24.4 | 19.7 | 103 |
|                | Achard et al. (2004) | | | | 35 |
|                | Pan et al. (2011) | 807 | 403 | 242 | 121 | 526 | 263 | 1575 | 496 |
| 2000–2010      | Our study with Average Baccini/Saatchi | 62.4 | 29.5 | 6.8 | 3.5 | 27.5 | 11.0 | 97 | 44 |
|                | Our study with Ecozone map | 63.4 | 5.1 | 20.7 | 89 |
|                | Pan et al. (2011) | 858 | 429 | 271 | 135 | 593 | 297 | 1722 | 539 |
|                | Baccini et al. (2012) for period 2000–2005 | | | | | | | |

Table 3 Annual Carbon removals from forest regrowths accumulated over one decade for periods 1990–2000 and 2000–2010 (values in 10$^6$ tC yr$^{-1}$).
our study (only when deforestation is following degradation).

Compared to the most recent pan-tropical or global studies (Baccini et al., 2012; Harris et al., 2012b; Pan et al., 2011), we use spatial information on forest cover changes at a much higher spatial detail although limited to a sample of ca. 4000 sites (indeed only Harris et al., 2012b used a rigorous spatial approach combining deforestation and biomass maps at 1 km resolution followed by a detailed error propagation approach). Through our more detailed spatial approach, we provide a more direct and robust approach for producing estimates of carbon losses and removals from land-cover changes in tropics and we reconcile the significant regional differences in recent low estimates of carbon emissions (Table 5).

Recent estimates of removals from tropical regrowth from Pan et al. (2011) at $1.57 \pm 0.50$ and $1.72 \pm 0.54$ MtC yr$^{-1}$ for the 1990s and 2000s, respectively or gross uptake of carbon in the fallow cycle of shifting cultivation from Baccini et al. (2012) at $0.71$ MtC yr$^{-1}$ for early 2000s fall outside our range of estimates at $0.12 \pm 0.05$ and $0.10 \pm 0.04$ MtC yr$^{-1}$ for the 1990s and 2000s, respectively (Table 3). Indeed, our

| Source Region | Baccini et al. (2012) 2000–2005 | Harris et al. (2012a) 2000–2005 | Eva et al. (2012) 2000–2005 | This study 2000–2010 |
|---------------|---------------------------------|---------------------------------|---------------------------|---------------------|
| South America | 4.88                            | 4.87                            | 4.40 (SE 0.32)            | 3.91 (SE 0.24)      |
| Africa        | 3.61                            | 1.89                            | n/a                       | 1.84 (SE 0.12)      |
| Southeast Asia| 1.23                            | 1.78                            | n/a                       | 1.90 (SE 0.18)      |
global estimates of carbon removals from forest regrowth in the tropics are five to fifteen times lower than these earlier estimates. These discrepancies might be interpreted partly by removals from tropical forests that are recovering from logging which are not included in our study, but also partly by the use of a spatial approach with spatially more detailed values of biomass increment in our study compared to the use of a nonspatial book keeping model with national or continental values in these previous studies. Although our estimates of carbon removals from tropical regrowth are much lower than those of Pan et al., 2011, it may not imply large differences for the overall carbon fluxes budget. Indeed, the large potential overestimation of carbon removals by Pan et al. (2011) can be compensated in the net flux by a similar overestimation of carbon losses. In particular, the global estimate of tropical emissions from land-use changes for the 2000s from Pan et al. is much higher than ours (2.82 ± 0.45 and 0.88 ± 0.32 MtC yr⁻¹, respectively) and this difference cannot be only explained by the inclusion of emissions from forest degradation in Pan et al. estimate.

Spatial patterns of forest cover, forest cover changes and carbon losses

Our results show the importance of carbon losses from forest and woodland clearance in tropics. The study allows also highlighting spatial and temporal patterns of forest cover, forest and OWL losses (Figs 1 and 2) and carbon losses resulting from these changes (Fig. 3). The main area of forest loss in both periods was in the so called ‘arc of deforestation’ of the Brazilian Amazon and in insular Southeast Asia (Sumatra and Borneo islands). Losses in OWL were geographically more widespread, with high losses occurring in the Brazilian states of Mato Grosso and Tocantins and in most of the dry African domain. Spatial patterns of forest regrowths and OWL gains (see Figure S1 in the Supporting Information) show the dynamics of forest plantations in Southern Brazil, Indonesia and Malaysia, and an important reduction in regrowths for the second decade in Africa.

Our study produces updated estimates of forest cover changes in the tropics and related carbon losses up to year 2010 (Fig. 4). We reduce uncertainties in such estimates through the use of satellite imagery at a much finer spatial detail than previous information available for period 2000-2005 (Hansen et al., 2010) used in other recent pan-tropical studies and the use of the two existing pan-tropical biomass maps (Baccini et al., 2012; Saatchi et al., 2011). The future priorities for the reduction in uncertainties in estimates of carbon emissions from land-use changes in the tropics lie in the improvement of regional forest inventories for assessing carbon content at local scale (Mitchard et al., 2013) and in the improvement of methods for the assessment of forest degradation, possibly with the use of remote sensing technology for both.

Acknowledgements

The vast majority of Landsat satellite data used in the study is coming from the GLS datasets (Global Land Survey) of the United States Geological Survey (USGS). Additional Landsat satellite imagery for years 1990 and 2000 were provided by ACRES (Australia), GISTDA (Thailand) and INPE. Complementary imagery (in particular for year 2010) was received from Astrium/French Development Agency (SPOT) and from the European Space Agency (AVNIR-2, Deimos-1, Kompsat, and RapidEye satellites) in the context of the TropForest project.

The authors would like to thank a large number of local forestry experts from the three continents for their support in reviewing the Landsat mapping results in the context of regional workshops (FAO/JRC, 2012).

The authors would also like to thank Javier Gallego of the JRC for his advices and contribution to the statistical aspects.

Finally, the authors would like to thank Scott Goetz of the Woods Hole Research Center for providing access to the full pan-tropical map of forest carbon density of Baccini et al. (2012) which is also available at http://www.wwhrc.org/mapping/panropical/ carbon_dataset.html. The carbon stock map of Saatchi et al. (2011) is available at http://carbon.jpl.nasa.gov.

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