Carbon emissions from forest loss in protected areas

A report commissioned by The Nature Conservancy as part of the PACT 2020 Innovation Initiative in collaboration with UNEP-WCMC and the IUCN World Commission on Protected Areas

September 2008

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This report was commissioned by The Nature Conservancy as a contribution to understanding the role of protected areas in responses to climate change. Under the auspices of IUCN, a number of partners including UNEP-WCMC and The Nature Conservancy are promoting an initiative known as PACT 2020 (Protected Areas and Climate Turnaround) to make the case for protected areas to be an integral component of responses to both climate change mitigation and adaptation. This report is an element of the foundational phase of this initiative that will be further developed as an IUCN Innovation Fund programme.

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Citation: Campbell A., Kapos V., Lysenko I., Scharlemann J.P.W., Dickson B., Gibbs H.K., Hansen M., Miles L. 2008. *Carbon emissions from forest loss in protected areas.* UNEP World Conservation Monitoring Centre.

Acknowledgements: This work has been supported by The Nature Conservancy.

With thanks to Charles Besancon and the protected areas team at UNEP-WCMC for encouragement in undertaking this project and support in the use of the World Database of Protected Areas

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Executive summary

Forest clearance contributes 20% of total global emissions of carbon dioxide (CO_2) to the atmosphere (IPCC 2007). Reducing forest loss is therefore of utmost importance for climate change mitigation. As formally protected areas are one potential tool for achieving these emissions reductions, it is important to understand the extent to which protected areas are in fact subject to land use change, and whether improving the effectiveness of their management could contribute to reducing emissions from deforestation and forest degradation.

This study combines the best available data on carbon stocks and deforestation with protected area data to estimate the area of forest loss within the protected area network of the humid tropical forest biome during 2000-2005. Carbon emissions resulting from deforestation are estimated according to four scenarios of land use following clearance; ranging from complete loss of biomass to pasture, crop, or oil palm development on a regional basis. Regions where protected areas are simultaneously rich in carbon and under pressure from land cover change are identified.

We examined the distribution of an estimated 21 million hectares of humid tropical forest loss between 2000 and 2005 (representing a 2% reduction in forest cover). The largest forest area loss was observed in the Neotropics. Rates of deforestation were similarly high in the Neotropics and Tropical Asia, 2.39 and 2.17% respectively. During the same period, over 1.7 million ha were estimated to have been cleared within protected areas in the humid tropics (0.81% of the forest they contained). Tropical Asia had the highest rates of deforestation within protected areas (1.33%). Despite low deforestation rates in protected areas in the Neotropics (0.79%), more than half the global total loss of humid tropical forest from within protected areas occurred in this region because of the large amount of forest protected there. Globally, more strictly protected areas (IUCN management categories I-II) had lower rates of humid tropical forest loss (0.53%) than the protected area network as a whole.

Protected areas of the humid tropical forest biome contained an estimated 70Gt of carbon in 2000, over half of which was in the Neotropics. We estimate that forest loss from within protected areas between 2000 and 2005 resulted in 822 - 990 Mt of CO_2 equivalent emissions. This accounted for around 3 % of total annual emissions from tropical deforestation during that period (IPCC 2007). Approximately 75% of total emissions from deforestation in protected areas were from the Neotropics with up to 15% coming from Tropical Asia. In both of these regions reducing deforestation in protected areas could provide significant emissions reduction benefits.

Improving the effectiveness of protected area networks, particularly in regions like the Neotropics and Tropical Asia that have large carbon stocks subject to high deforestation pressures, could be an important strategy for reducing emissions from deforestation and degradation.

Introduction

In addition to containing as much as 90% of terrestrial biodiversity (Brooks *et al.* 2006), tropical forests store more than 320 billion tonnes of carbon (Gibbs *et al.* 2007). Clearing these forests results in large emissions of carbon dioxide (CO_2) to the atmosphere; the annual emissions from current tropical deforestation have been estimated at ~1 – 2 gigatonnes (Gt; Ramankutty *et al.* 2007) or 20% of total global CO_2 emissions (IPCC, 2007). Reducing forest loss is therefore of utmost importance for climate change mitigation, and this is reflected in the commitment to include reduced emissions from deforestation and degradation (REDD) in the post-2012 agreements of the UNFCCC.

Achieving these emissions reductions will require effective strategies for reducing land cover change, in which formally protected areas are one promising tool. Protected areas, which are by definition designated with the primary aim of conserving biodiversity, generally constitute legal restrictions on land use change, and potentially play an important role in maintaining terrestrial carbon stocks. It has been estimated that globally, ecosystems within protected areas store over 312 Gt carbon or 15% of the terrestrial carbon stock (Campbell *et al.* 2008).

Despite their legal status, designation of protected areas does not in itself guarantee protection of the ecosystems they contain. Recent research indicates that whilst protected areas generally reduce deforestation relative to unprotected areas, they do not entirely eliminate land use change within them (Clark *et al.* 2008). Therefore, it is important to understand the extent to which protected areas are in fact subject to land use change, and the degree to which improving the effectiveness of existing protected areas could make an effective contribution to reducing emissions from deforestation and forest degradation

This study uses an analysis of new data on deforestation in the humid tropics to estimate deforestation within protected areas between 2000 and 2005. These estimates are used in combination with analysis of data on carbon stocks to identify regions where protected areas are simultaneously rich in carbon and under pressure from land cover change.

The principal reasons for tropical deforestation are conversion to cropland and pasture at both small and large scales (Geist & Lambin 2002, Lambin *et al.* 2001). However, the causes of deforestation differ among tropical regions (Rudel 2007). Pasture expansion is a major cause of deforestation (Chomitz *et al.* 2006, Steinfeld *et al.* 2006), especially in Latin America, where it has been the most important cause of forest loss over the last decade (Kaimowitz *et al.* 2004, Laurance *et al.* 2004, Nepstad *et al.* 2006a, Soares-Filho *et al.* 2006, Nepstad *et al.* 2008). Recently soybean production has become one of the most important contributors to deforestation in the Brazilian Amazon (Cerri *et al.* 2007). It has been estimated that by 2015, approximately 60% of the newly deforested area in the Brazilian Amazon will be used for soybean cultivation (Cerri *et al.* 2007), though much of that land will first have passed through a phase of use as cattle pasture (Morton *et al.* 2006). Rapid growth in consumption of vegetable oils both for food and biodiesel (OECD, FAO 2007) is driving rapid expansion of oil palm plantations. The total oil palm area in Indonesia expanded by more than an order of magnitude between 1967 and 2000, from less than 2000 km^2 to over 30,000 km^2 (FWI/GFW 2002), with much of this area derived from deforestation.

These different land uses all have different implications for estimating the amount of carbon emissions resulting from deforestation, which must include the release of carbon stored in the above ground biomass, decomposition of roots and mobilization of soil carbon, and must take account of carbon stored in subsequent land use. This study has applied some simple scenarios of likely regional land use changes to estimate the range of carbon emissions that may have resulted from deforestation in protected areas in different parts of the humid tropics.

These estimates can be used to make an initial identification of regions where improved investment in protected area networks would contribute to the UN Framework Convention on Climate Change (UNFCCC) goal to reduce emissions from deforestation and forest degradation.

Quantifying the emissions from deforestation also makes it possible to estimate the financial value of the carbon loss from protected areas within the humid tropical forest biome between 2000 and 2005, based on current market values. This may provide some indication of the scale of financial resources that could potentially be generated by including emissions from protected areas in a mechanism aiming to reduce emissions from tropical deforestation.

Protected areas are likely to make up just part of a national REDD strategy, and the role of the existing protected area network within a REDD mechanism is still subject to debate. However, carbon has a value on the international market place, and reducing deforestation within vulnerable protected areas could contribute towards national commitments on biodiversity conservation as well as on greenhouse gas emissions. As deforestation is already illegal in most protected areas, action can often be taken quickly without further legislation.

This study illustrates the potential role of protected areas in climate change mitigation and will be a useful input to current discussions on a mechanism for reducing emissions from deforestation (REDD) under the UNFCCC, which has also been raised within the UN Convention on Biological Diversity (CBD).

Methods

Study area

All analyses were restricted to the humid tropical forest biome, defined as all WWF ecoregions with humid tropical forests (Olson *et al.* 2001). Land clearing in the humid tropical forest biome results in a large loss of carbon stock, and includes highly biodiverse terrestrial ecosystems (Hansen *et al.* 2008).

Datasets

We estimated carbon loss within protected areas, and its financial value, by combining spatial datasets on forest area, forest area loss from 2000 to 2005, carbon stock, protected areas and a dataset of carbon market prices.

Forest area

We calculated forest area for the year 2000 from the Vegetation Continuous Field (VCF) tree cover data gathered by the MODerate Resolution Imaging Spectroradiometer (MODIS) at 500m resolution (Hansen *et al.* 2003, 2006). MODIS provides the best available cloud-free observations at near daily repeat frequency globally. MODIS-derived VCF data provide information on percent tree canopy density per 500m pixel, which we converted to percent forest cover by dividing VCF by 0.8 to account for the fact that VCF observations are of tree canopy cover and not forest cover (completely forested pixels are recorded as 80% VCF canopy cover; Hansen *et al.* 2003). Further, to exclude non-forested pixels with some canopy cover (such as shrublands), we defined forest as pixels with ≥ 25% forest cover (Figure 1). We calculated forest area by multiplying the proportion of forest cover by the pixel area (21.47 ha; although notionally 500m resolution, each MODIS pixel is 463.3127 m squared).

Forest area loss 2000-2005

We estimated forest area loss between 2000 and 2005 from MODIS-derived change probability maps provided by Hansen and colleagues (Hansen *et al.* 2008). Hansen *et al.* employed a classification tree bagging algorithm to produce a 5-year change probability map at 500m resolution, based on 32-day MODIS composites of 7 spectral bands each (blue, green, red, near infrared and three mid infrared bands) and MODIS Land Surface Temperature. The classification tree algorithm related forest cover loss training data to the MODIS inputs and resulted in a per 500m pixel 5-year change probability map (Figure 2). We calculated the gross forest area loss by multiplying the change probability and the forest area within each 500m pixel (Figure 3).

Figure 1. Forest cover within the humid tropical forest biome in the year 2000, derived from MODIS Vegetation Continuous Field data at 500m resolution. Data from Hansen *et al.* (2008) shown in MODIS Integerized Sinusoidal projection. .

Figure 2. Probability of forest cover change within the humid tropical forest biome from 2000 to 2005, derived from MODIS data. Data provided by Hansen and colleagues (pers. comm.) shown in MODIS Integerized Sinusoidal projection.

Figure 3 Forest area loss within the humid tropical forest biome from 2000 to 2005, derived from MODIS data provided by Hansen and colleagues shown in MODIS Integerized Sinusoidal projection. Area loss is calculated as the product of forest area and probability of forest loss, and displayed as hectares of forest lost during 6 years per 100ha of land surface.

We note that MODIS data alone are inadequate for accurate estimation of forest loss because most forest clearing occurs on a smaller spatial scale than can be detected by MODIS. High spatial resolution Landsat data (28.5m resolution) allows for more accurate detection of cleared forest areas. However, as Landsat data have low repeat coverage, frequent cloud contamination, and are expensive to acquire, Hansen *et al.* (2008) integrated MODIS and samples of Landsat data to calibrate and derive a more accurate estimate of the forest area cleared aggregated at coarser resolution. Although these calibrated estimates at 18.5km resolution provide more accurate forest loss estimates, the spatial resolution is too coarse to permit investigation of forest loss within individual protected areas. We therefore used the 500m resolution forest area loss, derived from MODIS data alone in our analyses, recognising that this will underestimate actual forest loss.

Carbon stock

A map of total carbon stock (Figure 4) in terrestrial ecosystems within the humid tropical forest biome was produced by combining spatially explicit datasets for biomass carbon (Ruesch & Gibbs, in review) and soil carbon stock (IGBP-DIS 2000).

The biomass carbon stocks of natural ecosystems used in this analysis were estimated using the Intergovernmental Panel on Climate Change (IPCC) Tier-1 approach (IPCC 2006, Gibbs *et al.* 2007). First, IPCC default values for the humid forest ecoregions for each continent were used to estimate above ground biomass carbon stocks. Then, below-ground biomass was estimated using the IPCC root-to-shoot ratios by vegetation type and ecoregion (IPCC 2006). Lastly, biomass values were converted to carbon stocks using the carbon fraction for each vegetation type (0.47 for most forests). Time-averaged carbon stocks for cropping systems were estimated by assuming linear growth rates, and using half the peak carbon stock (van Noordwijk *et al.* 1997). Applying these below- and above-ground carbon estimates to the best available global land cover map at 1km resolution (GLC2000; EC-JRC 2006, Bartholome and Belward 2005), Ruesch & Gibbs (in review) produced the most up to date global biomass carbon stock map, following IPCC Good Practice Guidance for reporting greenhouse gas emissions.

The organic soil carbon dataset produced by IGBP (IGBP-DIS 2000) provides estimates of organic carbon density to 1m depth at 5 minute spatial resolution. These data are appropriate for estimating soil carbon emissions from land conversions in most cases, but probably underestimate carbon emissions from deeper peatland systems. Although a finer spatial resolution soil dataset exists (Harmonised World Soil Database at 1km resolution; FAO/IIASA/ISRIC/ISS-CAS/JRC, 2008), these data appear to underestimate peatland soil in Indonesia to a greater extent than the IGBP estimate.

Figure 4. Total carbon stock derived by combining biomass carbon (Ruesch & Gibbs, in review) and organic soil carbon (IGBP-DIS 2000). Projected to MODIS Integerized Sinusoidal projection, spatial resolution 1km.

Protected areas

Protected area data were obtained from the World Database on Protected Areas (WDPA; UNEP-WCMC and IUCN, 2007), which holds spatial and attribute information on over 120,000 nationally and internationally protected sites. We confined these analyses to all sites within the WDPA that had spatial boundary data. Protected areas without information on their gazetted boundaries were excluded as a lack of spatial data prevents accurate estimation of forest loss. We further excluded those protected areas known to have been established after 1999 as we were interested in investigating forest and carbon loss from 2000-2005 within established protected areas. We included 5,787 protected areas located in the humid tropical forest biome in our analyses.

We distinguished two classes of protected areas based on the degree of permitted resource use, as identified by the International Union for the Conservation of Nature (IUCN) management categories. Any protected area must have biodiversity conservation as a major aim, but the degree of permitted use varies. We analysed data separately for protected areas in IUCN management categories I and II (where use is more restricted), and for all protected sites within the WDPA, including protected areas within IUCN management categories I-VI and those not assigned to an IUCN management category, such as forest reserves (Figure 5).

Financial value of carbon

To estimate the financial value of the carbon lost to deforestation in protected areas we compiled data on market prices for forest carbon. Carbon prices vary among regions and projects, as well as over time, so any single value for carbon stored in forests should be considered as notional, particularly given that the scale of the market will be strongly influenced by REDD implementation.

Forestry projects have consistently commanded prices at the higher end of the range in the voluntary market, with weighted average prices reported at US$6.8 to $8.2 per tCO_2e (Hamilton *et al.* 2008; Table 1). The average price for avoided deforestation projects is $4.8 (range $2- $30), soil carbon credits attract $3.90 on average. It is not clear whether the avoided deforestation projects included on the voluntary market avoided emissions from soil. Smith & Scherr (2002) concluded that market price estimates will likely fall within an optimistic $8-40 range. However, Neef *et al.* (2007) maintain that with few market signals available for forest carbon, the most reliable price remains that established by the BioCarbon Fund of $4. Others report that a price for stored carbon of $10 is more realistic, and could increase over the coming decades (Laurance 2007).

Figure 5. Protected areas within the humid tropical forest biome included in the analysis. Those in IUCN management categories I-II are shown in green and all other protected areas are shown in yellow. Data provided by the WDPA (UNEP-WCMC and IUCN, 2007), projected to MODIS Integerized Sinusoidal projection, spatial resolution 500m.

Table 1. Reported market prices for carbon in the forest sector. Price of land-based offsets. Adapted from Kollmuss *et al.* (2008), Taiyab (2006), Hamilton *et al.* (2008)

Offset	Project type	Price (US$/$tCO_2e$)
Chicago Climate Exchange (CCX)*	All (mostly soil carbon)	$1.5-3
Voluntary Market	Forestry	$6.8 - $8.2/
	Avoided deforestation	$4.8 (range $2- $30)
Climate, Community and Biodiversity standards (NGOs and large corporations)	LULUCF	$7-15
Plan Vivo (NGOs)	LULUCF	$3.5-14
Climate Care (UK)	Community based energy, some forestry	$12
Conservation International	Avoided deforestation	$5
	Forest restoration	$8-12
Face Foundation	Forestry	$15-19
Future Forests	Forestry	$12
Green Fleet	Australia	$8
Primaklima	Forestry	$2
Scolel de Te	Avoided deforestation, Mexico	$10-12
New Forests	Avoided deforestation for VERs, PNG	$3-11

***Values on CCX have risen in early 2008 so this range is likely an underestimate**
**** Values converted to dollars in some cases**

Our review of forest carbon market prices and the voluntary carbon market suggest that the value of forest carbon is likely to range from $1–15. Within this, it is considered that a range of $5-10 is the most likely range for forest carbon, $5 being a conservative estimate considering that certification schemes will raise the price in some cases, and assuming that avoided deforestation is tested on the voluntary market for formalization in the UNFCCC. The mid-range estimate is therefore $7.50, with $10 considered the top end of the scale as an average value.

To convert our estimates of carbon loss (in tonnes) to financial values, we multiplied tonnes of carbon by the conversion factor 3.66 to obtain tCO_2e (IPCC 2007). The CO_2 equivalent tonnes are then multiplied by $7.50 per tCO_2e to provide an estimate of the total financial value of carbon emissions.

Carbon loss within protected areas

All spatial data were projected to the equal-area MODIS Integerized Sinusoidal projection and rasterised to 500m resolution. Forest area and loss and carbon stock in biomass and soil were clipped to the protected area layer and the data summarized by biogeographic realm for the two protected area classes. We further summarized data for the entire humid tropical forest biome.

Carbon loss estimates require assumptions about the carbon remaining or carbon found in the replacement vegetation once the forest has been cleared. The potential for emissions of carbon from standing biomass removed in forest clearance is obvious. What may be less obvious is that conversion from tropical forest to agriculture has implications for carbon stored in soil. Research has suggested that soil carbon accounted for 28% of net loss from land use change in the period 1850-1990 (Houghton 2005). Although conversion often leads to a decreases in soil carbon, estimates of such changes are extremely variable and depend upon the crop type, the management of the land post-conversion, and the year and depth of sampling (Murty *et al.* 2002). In most cases, changes in soil carbon will likely be small relative to changes in vegetation carbon stocks (Brown 2002), but significant emissions have been estimated from conversion of other ecosystems with a high organic matter content in the soil, such as peat swamp forests (e.g. Hooijer *et al.* 2006). For soil carbon, it is estimated that 25% is lost on conversion to agricultural systems, and 10% is lost on conversion to oil palm plantations. These figures are likely to underestimate the impacts of conversion on soil carbon in peatlands (Hooijer *et al.* 2006). Soil carbon losses from pasture have not been included due to a lack of adequate global statistics and to the strong influence of management practices.

Here we present four scenarios with the following carbon loss assumptions:

Scenario 1: Forest clearance has removed all above- and below-ground biomass carbon whereas the soil carbon has remained unchanged.

Scenario 2: Cleared areas have been converted to pasture in all regions. Soil carbon has remained unchanged.

Scenario 3: Cleared areas have been converted to pasture in the Neotropics and Afrotropics, whereas in Tropical Asia and Australasia oil palm plantations are grown on the cleared lands. Soil carbon has remained unchanged under lands converted to pasture, but 10% of soil carbon was lost during conversion to oil palm plantations.

Scenario 4: Cleared areas have been converted to arable crops in the Neotropics and Afrotropics, whereas in Tropical Asia and Australasia oil palm plantations are grown on the cleared lands. During conversion to arable crops and oil palm plantations, 10% and 25% of soil carbon was lost respectively.

For these scenarios, carbon loss is estimated by assuming that all biomass carbon in the forest is emitted to the atmosphere as CO_2 over the long term (Fearnside 1997). The soil carbon loss and carbon stocks in biomass for each of the land uses in the scenarios are based on the best available estimates (Table 2). In parts of tropical Asia, where the GLC2000, the basis of the carbon map, underestimated forest area compared to MODIS, we applied a carbon stock correction.

Table 2 Remaining carbon stocks in the four scenarios for modified tropical landscapes (adapted from Gibbs *et al.* in review).

Land use change scenario	Neotropics remaining carbon stock		Afrotropics remaining carbon stock		Tropical Asia remaining carbon stock	
	Biomass (tC/ha)	soil % original	Biomass (tC/ha)	soil % original	Biomass (tC/ha)	soil % original
Scenario 1	No biomass		No biomass		No biomass	
	0	100	0	100	0	100
Scenario 2	Pasture		Pasture		Pasture	
	8	100	8	100	8	100
Scenario 3	Pasture		Pasture		Oil palm	
	6	100	8	90	88	90
Scenario 4	Crop		Crop		Oil palm	
	6	75	4	90	88	90

Whilst these four scenarios are based on general drivers of deforestation within each region, they are less likely to represent actual land use change, especially within protected areas. Despite this, they define a range of plausible scenarios. Scenario 1 is the 'worst case' in assuming that no biomass carbon remains following deforestation, but this may be offset by the assumption that soil carbon remains intact. Scenarios 2-4 recognise that conversion to cropland and pasture are the principal drivers of tropical deforestation (Geist & Lambin 2002, Lambin *et al.* 2001). Pasture is taken as the most likely land use in Scenario 2 as this is a well documented driver of deforestation (Chomitz *et al.* 2006, Steinfeld *et al.* 2006), particularly in Latin America (Kaimowitz *et al.* 2004, Laurance *et al.* 2004, Nepstad *et al.* 2006a, Soares-Filho *et al.* 2006, Nepstad *et al.* 2008). Oil palm plantations are considered the most likely land use conversion in Tropical Asia (FWI/GFW 2002), where the total area under oil palm expanded greatly from 2000 to 2005 (Figure 6). Land area under arable crops has also increased in each region (Figure 6) and such conversion is likely to account for a significant proportion of the deforested area, especially in Latin America, as reflected in scenario 4. The fact that cropland is also often developed from pasture may explain the nearly constant area of pasture in all three regions (Figure 6).

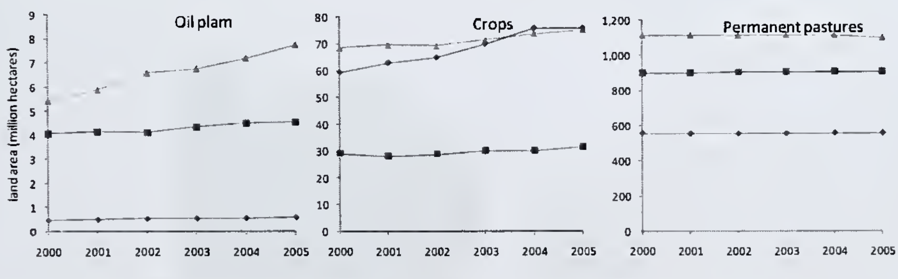

Figure 6. Change from 2000 to 2005 in the area of land (million hectares) under oil palm, crops (maize, sugar cane, and soybeans), and permanent meadows and pastures in Latin American (blue diamonds), Africa (red squares) and in Asia and Melanesia (green triangles). Data from FAOSTAT 2008.

Results

Humid tropical forest area and forest area loss

The humid tropical forest biome contained an estimated forest area of 1,108 million hectares in 2000, of which an estimated 21 million hectares (1.87%) were cleared between 2000 and 2005. The highest estimated rates of forest loss were observed in the Neotropics, with similarly high levels of deforestation in the tropical Asian realm (Table 3). While deforestation was lowest in African humid tropical forests, it is likely that the rate given here is an underestimate because much forest loss in Africa occurs in small patches and through degradation and this is poorly detected with imagery at the resolution of the MODIS data. The estimates in Table 3 are therefore conservative, especially for Africa. See Hansen *et al.* (2008) for regional clearing estimates based on analysis of samples of finer-scale Landsat data.

Table 3. Regional estimates of humid tropical forest area and forest loss between 2000 and 2005.

Realm	Forest area ('000 hectares)	Forest area loss ('000 hectares)	% forest loss
Neotropic	620,290	14,845	2.39
Afrotropic	185,752	444	0.24
Tropical Asia	220,964	4,792	2.17
Australasia	80,775	656	0.81
TOTAL	**1,107,780**	**20,737**	**1.87**
TOTAL sans Africa	922,028	20,293	2.20

Although protected areas appear to have been effective in reducing deforestation in the humid tropics between 2000 and 2005, having lost only 0.81% of their forest compared with forest loss of 2.13% outside protected areas (Figure 7, Table 4), it is clear that they were subject to significant deforestation pressure (Figure 7). We estimate that over 1.7 million ha of forest were cleared in tropical protected areas in 2000-2005 (Figure 7, Table 4).

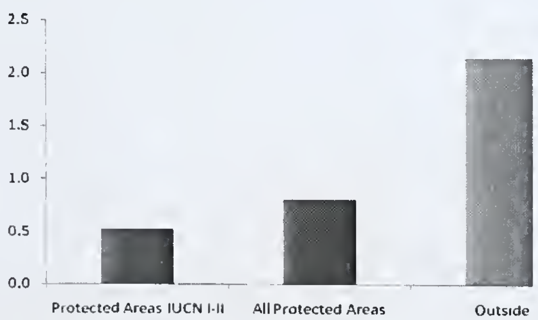

Figure 7. Estimated forest loss (in %) within protected areas and outside protected areas in the humid tropical forest biome. 'All Protected Areas' refers to all sites within the WDPA, excluding those known to have been established after 1999 and those with no spatial boundary data (and includes sites in IUCN management categories I and II). 'Outside' includes all other areas of forest in the humid tropical biome.

Protected areas in the Neotropics lost the greatest total area of forest (1.2 million ha; Table 4), which accounted for 71% of the total area of humid tropical forest loss from protected areas globally (Figure 8). However, proportional deforestation rates within protected areas of the Neotropics were low (0.8%) relative to the overall deforestation rate for the region (1.9%; Table 3, Table 4). The greatest percentage of forest loss within protected areas was in Tropical Asia (1.33%, Table 4; Figure 9), reflecting the limited extent of forests remaining in the region (Table 3) and the strong pressures to which they are subject.

Table 4. Humid tropical forest area and forest area loss between 2000 and 2005 within protected areas by realm. Data shown for strictly protected areas (IUCN categories I-II), all protected areas, and outside protected areas.

Realm/biome	Protection status	Forest area ('000 ha)	Forest loss ('000 ha)	% forest loss
Neotropic	Protected Areas IUCN I-II	44,725	214	0.48
	All Protected Areas	**156,702**	**1,240**	**0.79**
	Outside	463,587	13,605	2.93
Afrotropic	Protected Areas IUCN I-II	9,184	11	0.12
	All Protected Areas	**22,697**	**70**	**0.31**
	Outside	163,054	374	0.23
Tropical Asia	Protected Areas IUCN I-II	10,014	96	0.96
	All Protected Areas	**28,185**	**376**	**1.33**
	Outside	192,778	4,416	2.29
Australasia	Protected Areas IUCN I-II	3,998	37	0.92
	All Protected Areas	**9,616**	**64**	**0.67**
	Outside	71,158	592	0.83
Humid Tropical Forests	Protected Areas IUCN I-II	67,922	358	0.53
	All Protected Areas	**217,201**	**1,750**	**0.81**
	Outside	890,578	18,987	2.13
	Total	1,107,780	20,737	1.87

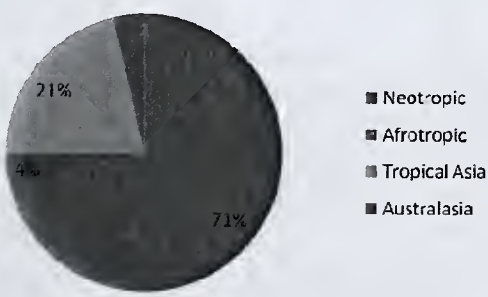

Figure 8. Regional contributions to total forest area loss from the protected areas of the humid tropical biome, 2000-2005

Regional patterns of estimated forest loss in protected areas were influenced not only by deforestation pressures, but by the nature of the protected areas themselves (and the effectiveness with which they were managed). In all regions forest loss was mostly concentrated near the edges of protected areas (Figure 10). Across the humid tropics, strictly protected areas (IUCN management categories I-II) lost less of their forest area (0.53%) between 2000 and 2005 than the whole range of protected areas (0.81%; Figure 7, Table 4), which included areas designated for various forms of resource exploitation. Strictly protected areas in humid tropical Africa had the lowest estimated rates of forest loss (0.12%; Figure 9). A high proportion of protected areas permitting resource use (e.g. forest reserves) may help to explain the higher proportion of estimated forest loss from within the full range of African protected areas compared to outside them.

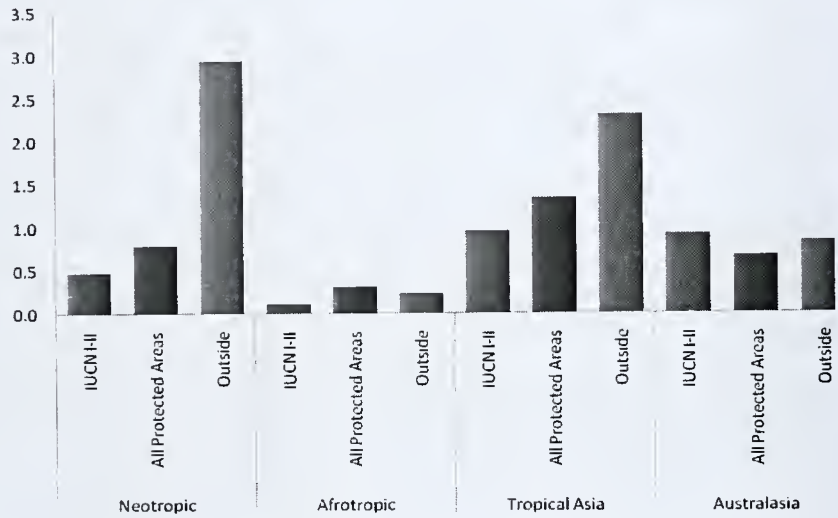

Figure 9. Forest loss (in %) within and outside protected areas in the four realms of the humid tropical forest biome.

Although deforestation rates in more strictly protected areas in Australasia (0.92%) appeared higher than deforestation in all types of protected area (0.67%) or outside protected areas (0.83%; Figure 9), this may be an artefact of the large number of protected areas in this region lacking boundary information, which are excluded from this analysis. It is also possible that category I-II protected areas in this region have been designated in areas of high deforestation pressure.

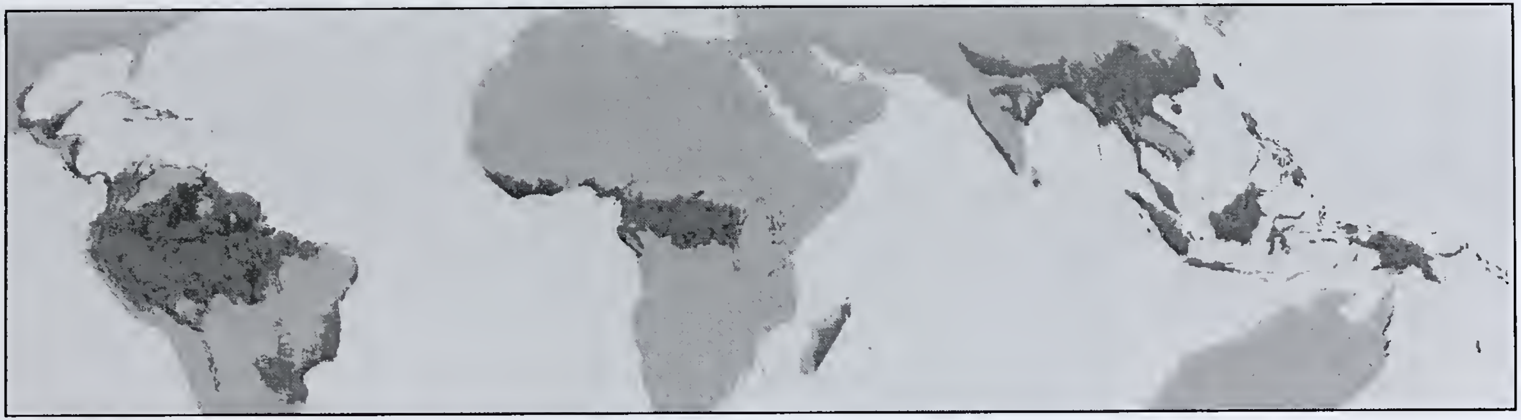

Figure 10. Forest area loss in all protected areas in the humid tropics, shown as hectares of forest lost per 100ha of land surface.

Loss of forest carbon within the tropical humid biome

In the year 2000, protected areas of the humid tropical forest biome contained an estimated 70 Gt of carbon (Table 5). Protected areas with high carbon density are found in parts of SE Asia and Papua New Guinea, the northern bands of tropical forest in Africa, and central and western regions of the Amazon Basin (Figure 11). The protected areas in the Neotropics had higher carbon stocks on average, totalling 48 GtC or more than twice the combined carbon stocks in protected areas of the other regions (Table 5). This reflects both the large extent of protected areas in the Neotropics and the high carbon storage within their vegetation and soils.

Table 5. Estimated carbon stocks within protected areas of the tropical humid biome

Realm	Biomass carbon (Mt)	Soil carbon (Mt)	Total carbon (Mt)
Neotropic	30,272	18,177	48,450
Afrotropic	4,742	3,007	7,750
Tropical Asia	4,603	4,652	9,255
Australasia	2,137	2,756	4,893
Humid Tropical Forests Total	41,755	28,593	70,348

Based on the estimated carbon stocks and forest area losses, we calculated that between 225 and 271 Mt carbon were lost from protected areas within humid tropical forests between 2000 and 2005, depending on the scenario used to represent land use following deforestation (Table 6). Strictly protected areas appear to have played a significant role in reducing carbon losses from humid tropical forests; 44-55 Mt or about 0.2% of carbon stock was lost from all category I-II protected areas within the humid tropical biome compared to about 0.4% loss of carbon stock from all protected areas (Table 6). This suggests that whilst management of the strictly protected areas could be improved, strengthening the management of other protected areas categories could make a valuable contribution to reducing carbon emissions due to deforestation.

Figure 11. Total carbon stock in 2000 in protected areas of the humid tropical forest biome.

Among the different scenarios, the loss of all biomass carbon (scenario 1) gives the greatest estimated total carbon loss (Table 6), but it differs relatively little from the scenarios involving establishment of pasture or crops because these scenarios include additional losses of soil carbon.

Table 6. Estimated potential total forest carbon loss (and percentage) within protected areas of the humid tropical biome between 2000 and 2005, by realm.

Realm	Carbon loss according to scenario MtC (%)			
	1	2	3	4
Neotropic	204 (0.42)	194 (0.40)	194 (0.40)	228 (0.47)
Afrotropic	11 (0.15)	11 (0.14)	11 (0.14)	13 (0.17)
Tropical Asia	43 (0.47)	40 (0.43)	10 (0.11)	10 (0.11)
Australasia	13 (0.26)	12 (0.25)	10 (0.20)	10 (0.20)
Humid Tropical forests IUCN category I-II	55 (0.25)	52 (0.24)	44 (0.20)	50 (0.23)
Humid Tropical forests all protected areas	**271** (0.38)	**256** (0.36)	**225** (0.32)	**261** (0.37)

In accordance with patterns of total forest area loss, the greatest total carbon loss occurred in the Neotropics for all of the scenarios (194-228 MtC; Figure 12), representing around 0.4% of the carbon stock in the region's protected areas (Figure 13), and 75-87% of the carbon potentially lost from humid tropical protected areas in 2000-2005 (Table 6 and Table 7). Much of this loss was concentrated near the edges of protected areas in the 'Arc of deforestation' in the Southern Amazon (Figure 14), with some areas of significant carbon loss also notable in Central America.

Table 7. Contribution of each region to the total forest and forest carbon loss within protected areas of the humid tropical biome.

Realm	**Forest area**	**Forest loss**	**Total carbon stock**	**Carbon Loss Scenario 1**	**Carbon Loss Scenario 4**
Neotropic	72.1	70.8	68.9	75.2	87.3
Afrotropic	10.4	4.0	11.0	4.2	5.0
Tropical Asia	13.0	21.5	13.2	15.9	3.9
Australasia	4.4	3.7	7.0	4.6	3.8
Total Humid Tropical Forests	100.0	100.0	100.0	100.0	100.0

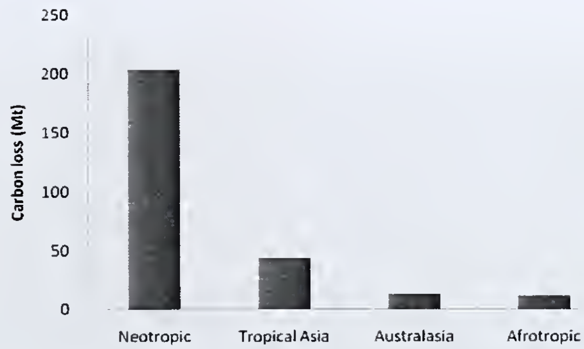

Figure 12. Total carbon loss from within protected areas during 2000-2005, by realm, based on scenario 1 where it is assumed that forest clearance results in complete biomass loss.

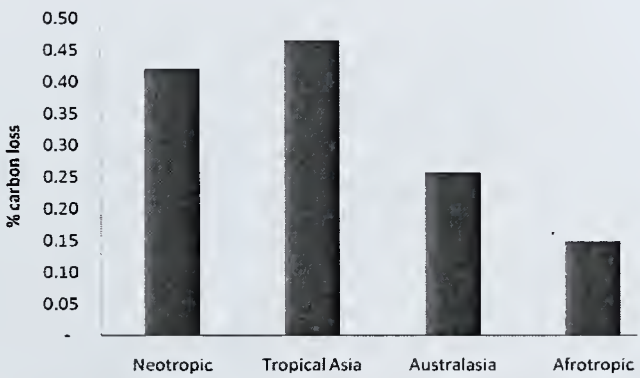

Figure 13. Percentage of forest carbon stocks lost within protected areas during 2000-2005 according to scenario 1 where it is assumed that forest clearance results in complete biomass loss.

Low levels of visible carbon loss in the Afrotropics (Figure 15) were in part due to the aforementioned difficulties of detecting deforestation in this region. For the scenarios involving complete biomass loss or pasture conversion, protected areas in Tropical Asia lost the highest percentage of their carbon stocks (0.4 - 0.5%; Figure 13; Figure 16), but the scenarios involving development of oil palm plantations showed much smaller estimated carbon loss in the region because of the relatively large amount of carbon stored in palm plantations (Table 6). However, scenarios 3 and 4 are likely to be underestimates as plantation development is likely to have been more limited in protected areas than in the region as a whole. While such uncertainties mean that these scenarios are a poor substitute for reliable data on land use change within protected areas, they provide a basis for calculating the range of possible emissions over the period 2000-2005.

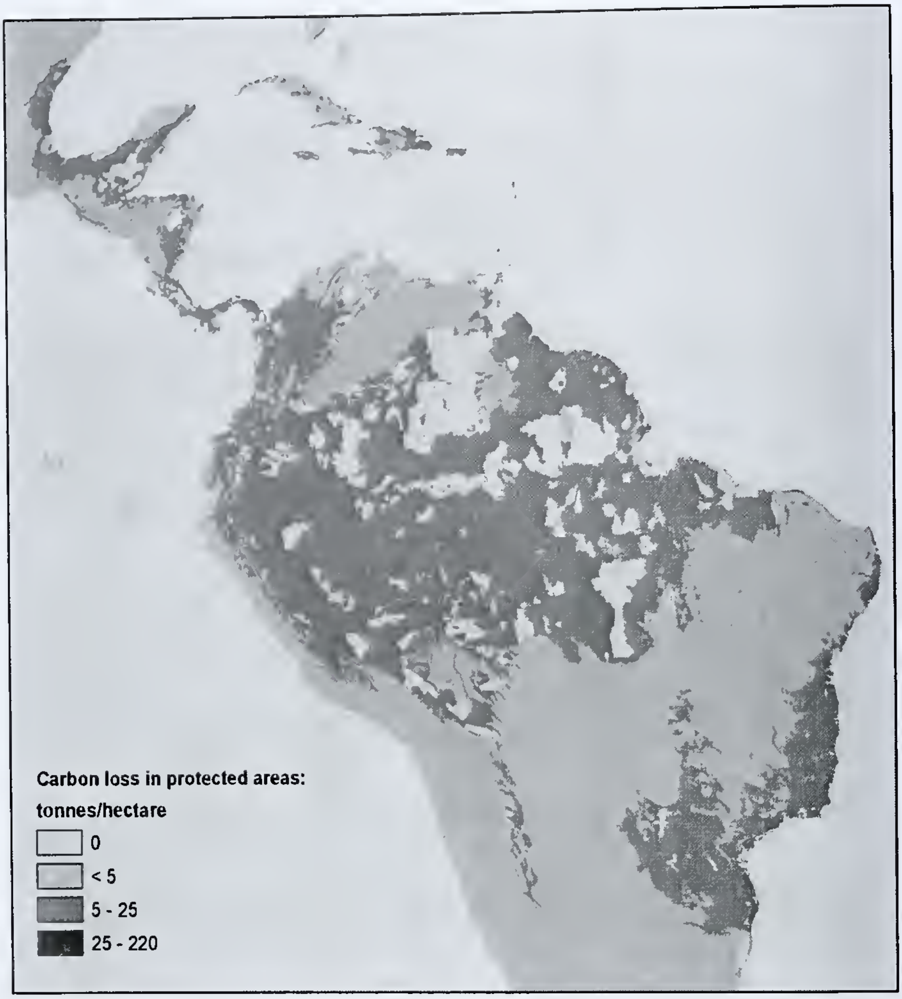

Figure 14. Carbon loss due to deforestation in protected areas of humid tropical forest in the Neotropics, 2000-2005. Calculated according to scenario 1, where all biomass is lost and not replaced by subsequent land use, but soil carbon remains intact.

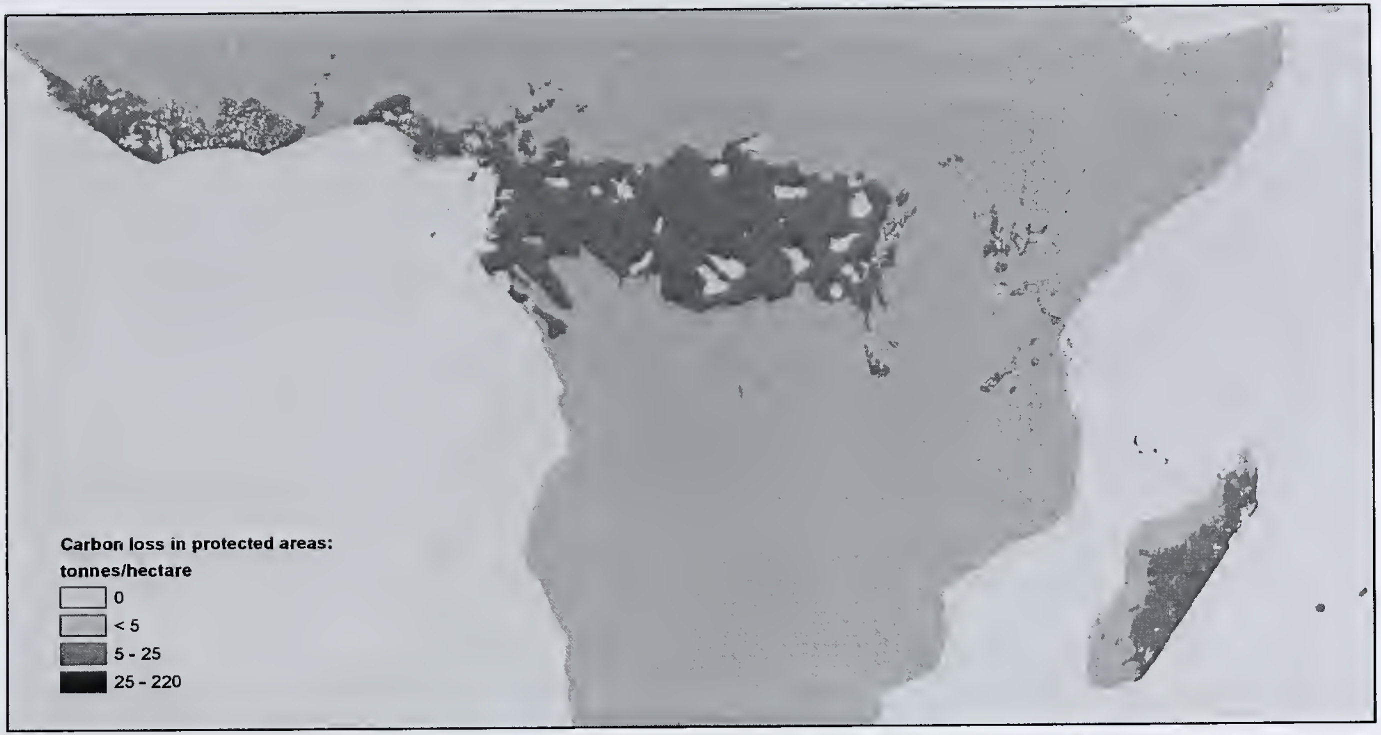

Figure 15. Carbon loss due to deforestation in protected areas of humid tropical forest in the Afrotropics, 2000-2005. Calculated according to scenario 1, where all biomass is lost and not replaced by subsequent land use, but soil carbon remains intact.

Figure 16. Carbon loss due to deforestation in protected areas of humid tropical forest in Tropical Asia, 2000-2005. Calculated according to scenario 1, where all biomass is lost and not replaced by subsequent land use, but soil carbon remains intact.

The carbon losses reported should also be viewed in the context of potential CO_2 emissions. An estimated 822-990 Mt CO_2 were emitted from within protected areas of the tropical humid biome from 2000-2005 (Table 8). The wide range of potential emissions from Tropical Asia again underlines the uncertainties of estimating emissions estimates from land use change scenarios.

Table 8. Estimated potential CO_2 emissions from deforestation within protected areas of the tropical humid biome between 2000 and 2005, by realm.

Realm	Range of emissions from scenarios 1-4 (Mt CO_2e)
Neotropic	709-834
Afrotropic	40-47
Tropical Asia	38-158
Australasia	37-46
Humid Tropical forests IUCN category I-II	160-203
Humid Tropical forests all protected areas	822-990

According to our calculations, if the carbon emissions from protected areas over the period 2000-2005 were to be valued on the basis of current market prices, they would have been worth between $4 and $10 billion (Table 9). Based on the 'most likely' carbon price of $7.50 per tonne CO_2e, carbon emissions from protected areas could potentially have had a value of $6.2 – 7.4 billion. While such market valuation is not directly applicable to reducing emissions on these scales, it gives some indication of the potential for economic impact arising from improving the management of protected areas.

Table 9. Notional financial value of carbon lost from protected areas of the humid tropical biome 2000-2005, based on current market prices. Values are based on the range of CO_2 emissions for three plausible prices of US$ per tonne.

	Notional value of emissions ($ billions)		
Market price (US$/tCO2e)	$5	$7.50	$10
Humid Tropical forests IUCN category I-II	0.8 – 1.0	1.2 – 1.5	1.6 – 2.0
Humid Tropical forests all protected areas	4.1 – 5.0	6.2 – 7.4	8.2 – 9.9

Discussion

The results of these analyses show that while the protected areas included in this study were subject to much lower rates of deforestation than humid tropical forests more broadly, they still lost appreciable amounts of forest and contributed as much as 990 Mt of CO_2 equivalent to global carbon emissions between 2000 and 2005, or around 3% of total emissions from tropical deforestation (IPCC 2007).

The vast majority (around 80%) of emissions from protected forests originated in the Neotropics, due to the combination of large areas of high-carbon protected forests and high rates of expansion of agricultural and pasture land (Nepstad *et al.* 2006, Soares-Filho *et al.* 2006, Nepstad *et al.* 2008). However, the rates of forest loss were considerably lower within than outside protected areas in this region. Tropical Asia had the highest deforestation rates in protected areas, rising above 1% during 2000-2005. This is due to a combination of high deforestation pressures on protected areas that are much less remote and a smaller total area of forest. Tropical Asia contributed around 15% of the total emissions from deforestation in protected areas in the humid tropics.

The deforestation estimates reported here for the humid tropical forest biome are likely to be underestimates, and are lower than those reported by Hansen *et al.* (2008) by approximately 6 million ha. This is because MODIS data are likely to underestimate deforestation in small forest areas with small scale forest loss, so Landsat-validated estimates are more accurate than those using MODIS alone. The present study's estimate for deforestation in the Afrotropics is particularly likely to be low due to the dynamics of forest change in this region, which is more likely to follow a pattern of degradation and small scale deforestation.

The scenarios used in this analysis are indicative only and do not reflect actual land use change, therefore the emissions estimates are also indications of the potential levels of emissions that could have resulted from deforestation over the period. For example, whilst oil palm plantation has been identified as a large scale driver of deforestation in Tropical Asia, and it is known to encroach on protected areas (Nelleman *et al.* 2007), the extent to which it has done so is unclear. Therefore, the carbon loss estimates for Tropical Asia are likely to be underestimates, as oil palm has a higher carbon stock than any alternative land use included in these scenarios.

Because protected forests of Tropical Asia have a large carbon stock and suffer high deforestation rates, improving the effectiveness of protected areas in reducing emissions in regions like South East Asia might reasonably be given high priority. Similarly, the high deforestation pressures causing relatively large amounts of carbon loss from protected areas in the Neotropics mean that improved management of protected areas in this region is also potentially of high priority. Limiting deforestation in category I-II protected areas of Australasia could also be a means of reducing emissions, particularly in Papua New Guinea, where protected areas have high carbon stocks.

While even strictly protected areas are not always entirely effective at halting forest loss, protected areas in IUCN management categories I-II in general had lower rates of forest loss than those observed in the overall protected area network. This finding, which is consistent with those of previous studies (Clarke *et al.* 2008), suggests that improving protected area management has the potential to reduce CO_2 emissions from deforestation. Strategies are especially needed to improve the effectiveness of protected areas in less restrictive management categories in reducing deforestation and resulting emissions. There is evidence that improved forest management strategies can greatly reduce carbon emissions (Putz *et al.* 2008), and might be more beneficial in carbon terms than imposing stringent restrictions on forest use, which might cause 'leakage' of deforestation into surrounding areas.

Indeed, leakage is an important issue not taken into account in this study. While protected areas may effectively reduce deforestation within their borders, there is a risk that deforestation pressures are merely displaced elsewhere, either to other areas of forest or to other ecosystems entirely. Although this study focused on deforestation within protected areas, it should be emphasised that 85% of the global carbon stock lies outside of the protected area network (Campbell *et al.* 2008, and in ecosystems other than forest) and it is vital from a climate change perspective that this carbon is managed appropriately. In addition, this study made no attempt to estimate emissions from forest degradation.

The estimates reported here are from global scale carbon stock data. Whilst this is useful for drawing wide scale conclusions and identifying regions in which carbon is being lost from protected areas, nationally available data will usually be more accurate than subsets from such standardised global datasets. Therefore analyses based on national or regional data sets would be more applicable at national scale and could provide useful inputs to the development of national REDD strategies. A review of regional data sources (Annex 1) has identified a number of existing regional data sets, but none that was feasible for inclusion in this study within the time available. Regional scale data could also be available that would support development of more accurate land use change scenarios.

Regardless of which land use scenario is applied, it is clear that protected areas suffered a substantial loss of forest area, and therefore carbon loss. Strengthening the protected area network, particularly in areas of high deforestation pressure and high carbon such as the Neotropics and Tropical Asia, could be one strategy to reduce emissions from deforestation and degradation.

Caveats

- The carbon estimates take little account of any forest reversion/regeneration, which is particularly likely on abandoned pasture and in regions with dynamic land use.
- Average carbon stock values have been used to estimate emissions. Consequently, forest carbon stocks and conversion emissions for a particular area may be overestimated or underestimated if the forests in question differ from the average forest strata values (Houghton 2005).
- Soil carbon losses from pasture have not been accounted for, due to a lack of adequate global statistics and to the strong influence of management practices. The impacts of post-conversion management in Amazonia were discussed by Fearnside & Barbosa (1998), who reported an 8-49% loss in soil carbon through conversion of forest to pasture with typical management, but a 3-58% gain in areas with ideal management practices. Indeed, it has been suggested that in the long term, pastureland has the same potential to store soil organic carbon as forest (Guo & Gifford 2002). Wetland and other peat soils are a special case with potentially large emissions following conversion that are difficult to prevent without restoration. Estimates of soil carbon emissions from deforestation are in general variable, and are a recognised inaccuracy in this report.
- Emissions of greenhouse gases other than carbon dioxide have not been estimated in this analysis.
- For these analyses, only MODIS 500m resolution probability of deforestation data were used. This is likely to be an underestimate as highlighted by Hansen *et al.* (2008). Coarser scale 18.5km data, validated with deforestation data from Landsat, would provide better estimates of deforestation but at much coarser scales.
- No buffer around protected areas was used. This decision was taken based on a review of the literature. Many recent studies that have compared deforestation rates inside and outside protected areas found that deforestation rates were higher in the surrounding 10km than inside the protected area (Sánchez-Azofeifa *et al.* 1999, 2003, Pelkey *et al.* 2000, Bruner *et al.* 2001, Deininger & Minten 2002, Helmer 2004, Curran *et al.* 2004, DeFries *et al.* 2005, Mas 2005, Naughton-Treves *et al.* 2005, 2006, Bleher *et al.* 2006, Nepstad *et al.* 2006b, Chowdhury 2006, Gaveau *et al.* 2007, Oliveira *et al.* 2007, Phua *et al.* 2008; Oliveira *et al.* 2007). As the purpose of our coarse scale analysis was to get some idea of the proportion of land under protection that is threatened by deforestation, it was considered that a buffer may give a misleading impression, under estimating the role of protected areas through inclusion of deforestation in the immediate surrounding areas. Indeed, studies in Costa Rica (Sánchez-Azofeifa *et al.* 2003) and Indonesia (Phua *et al.* 2008) found significant differences between deforestation rates inside the park and 1km outside of the park. For protected areas less than 21.4 ha (on MODIS 500m pixel), the lack of a buffer may mean that the pixel is classed as deforested, even though the protected area may be intact. The purpose of this study was not to compare deforestation rates within and outside of protected areas and the details of such comparisons should be treated with caution. For example, some areas of protected forest that were protected after 2000 and/or for which spatial boundary data were unavailable will have been considered as 'outside' of the protected area network in these analyses.

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Annex 1 Regional datasets

There are a number of national and regional estimates of carbon storage in tropical forest ecosystems. Such estimates tend to be more accurate than global estimates because they are extrapolated over smaller scales, rely on better inventory data, and can account for spatial variation in more detail. Optical sensing methodologies are also more accurate over regional scales. Many of the national level statistics are, however, difficult to obtain outside a particular country.

Given the importance of tropical forest deforestation in carbon fluxes, much of the national and regional analysis has focused upon the tropical forest ecosystems (Achard, 2004; DeFries *et al.* 2002; Houghton, 2003). Many studies have focused specifically on tropical forest within Latin America (Brown & Lugo, 1992, Fearnside & Laurance 2004, Chave *et al.* 2003, Baker, 2004, Malhi *et al.*, 2006, Saatchi *et al.*, 2007) with wide ranging results in carbon storage and distribution estimates (Houghton *et al.*, 2003). Other studies have focused on tropical Asia (Brown *et al.*, 1993; Chabra *et al.*, 2002) including one comprehensive study by Gibbs & Brown (2007a), updating estimates based on GIS processing of FAO georeferenced data onto the GLC 2000 land cover map. Relatively few carbon stock estimates have been carried out in Africa, the most comprehensive of which was provided by Gaston *et al.* (1998) and updated by Gibbs & Brown (2007b).

It should be noted that although regional estimates are more accurate than global scale estimates, there is still significant variation; with estimates for Zambia ranging from 1455-6378 MtC and Brazil from 54697 – 82699 MtC across the range of tropical forest studies (Gibbs *et al.*, 2007).

Latin America

A study by Houghton *et al.* (2001) has revealed wide discrepancies between seven biomass estimates in the Amazon, in both total carbon stored and the spatial distribution of forests. Two of the most recent regional studies for the Amazon basin are detailed below.

Malhi *et al.* (2006) built upon previous studies to estimate the spatial distribution of biomass of old growth forest in the Amazon from 226 forest plots. The study incorporated two of the three major carbon pools, but considered only old-growth forest. The purpose of the work was to determine regional biomass changes as a result of environmental factors to inform future work, and appears to have placed less emphasis on the actual total biomass estimates; local anomalies were removed to provide a smooth broad regional dataset. The study incorporated data and allometric relationships from a variety of other sources to estimate below-ground and dead biomass, as well as woody biomass <10cm diameter. However, the data improves on previous estimates and offers some useful insights into the current status of estimates for the Amazon. Perhaps the most interesting finding was that basal area and wood density were not concurrent, and indeed seemed to run in opposite directions, casting doubts over the accuracy of traditional biomass estimates.

Saatchi *et al.* (2007) estimated carbon stocks in Amazon Basin vegetation by combining data from biomass plots and remote sensing data (incorporating forest characteristics and environmental variables). This approach combines biomass estimates (limited in spatial coverage) with remote sensing for the entire region (limited in capacity for biomass estimation), improving the capacity of the predictive model. In contrast with other studies of the Amazon, biomass values were calculated according to all vegetation types present, such as old growth forest, floodplains, and small coastal patches. As with the previous Malhi *et al.* (2006) estimate, only above ground living biomass was estimated; total biomass was calculated using relationships to the other biomass types in the Amazon basin specified in published literature. Malhi (2006) did not account for degraded forest, but incorporated a potentially more accurate measure of biomass by recording both basal area and wood density; whereas the Saatchi *et al.* (2007) estimate improved the capacity of the predictive model by combining optical data with radar data. A direct comparison of the data for biomass in the Amazon basin by Saatchi *et al.* (2007) with that of the corresponding area from Reusch & Gibbs (in review) suggests that the latter is likely to underestimate carbon stocks.

Tropical Asia

One regional study of tropical Asia (Brown *et al.* 1993) used GIS processing of georeferenced data based on FAO inventories, and inferred land degradation from population densities to adjust carbon stock estimates. This data reflects the situation in 1980, and is only for forest at a coarse resolution, but includes an estimate of soil carbon. The study notes inadequate biomass data and imperfect regression equations as a limitation (Brown *et al.*, 1993). This methodology has been utilised in a recent update of forest carbon storage in tropical Asia (Gibbs and Brown 2007a). There are a limited number of studies in tropical Asia that do not use this data; a study of forest biomass in Borneo (Foody *et al.* 2001) had the primary aim of assessing biomass estimation methodologies, and did not calculate carbon stocks.

Tropical Africa

Relatively few carbon stock estimates have been carried out in Africa. Gaston *et al.* (1998) used the GIS processing methodology described above, combining spatially explicit estimates of biomass carbon density from GIS modelling with forest data from the FAO to estimate carbon storage in African tropical forest. Above and below ground carbon stocks were estimated, but no information is available on soil organic carbon (SOC) stocks. The most up to date vegetation carbon stock estimate for Africa (Gibbs & Brown, 2007a) was produced for year 2000 baseline stocks. The study improved on previous estimates by using the GLC 2000 land cover map and incorporating population pressure into the statistical model to account for land degradation (Gibbs & Brown, 2007a) Biomes were defined by FAO ecofloristic zones. The requirement for improved continental scale observations of carbon stocks in Africa has been highlighted.

Soil carbon estimates for tropical regions

Despite the fact that there is a substantial carbon store in the soils of tropical forest (41% of the total tropical carbon store according to Brown & Lugo, 1982), very few studies have estimated SOC for tropical regions. A number of estimates do exist for parts of Africa (Zinke, 2002; Batjes, 2004) and Brazil (Batjes 1999, 2005; Bernoux, 2002; Cerri *et al.*, 2007) but do not correspond to the geographical area covered by available carbon vegetation stock estimates

Table 10. Selected regional studies considered for use.

Region	Ecosystem	Carbon pool	Availability	Reference
Amazon Basin	All	Vegetation biomass	Readily available	Saatchi *et al.* (2007)
Amazon Basin	Old growth forest	Vegetation biomass DOM	Unknown	Malhi *et al.* (2006)
Brazilian Amazon	All	SOC	Readily downloadable	Cerri *et al.* (2007)
Tropical Africa	Forest	Woody Biomass	Available	Gibbs *et al.* (2007)
Southern Africa	Forest	SOC	Available	Zinke *et al.* (2002)
Tropical South East Asia	Forest	Vegetation biomass	Available	Brown *et al.* (2001) Gibbs *et al.* (2007a)
Tropical SE Asia	Forest	Vegetation biomass & SOC	Unknown	Brown *et al.* (1993)

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