Journal of Biogeography (J. Biogeogr.) (2006) 33, 491–505

SPECIAL ISSUE

A global overview of the conservation status of tropical dry forests

Lera Miles[1]*, Adrian C. Newton[2], Ruth S. DeFries[3], Corinna Ravilious[1], Ian May[1], Simon Blyth[1], Valerie Kapos[1] and James E. Gordon[4]†

[1]UNEP World Conservation Monitoring Centre, Cambridge, UK, [2]School of Conservation Sciences, Bournemouth University, Talbot Campus, Poole, Dorset, UK, [3]Department of Geography, University of Maryland, College Park, MD, USA, and Earth System Science Interdisciplinary Center, College Park, MD, USA and [4]Department of Geography, University of Durham, Durham, UK

*Correspondence: Lera Miles, UNEP World Conservation Monitoring Centre, 219 Huntingdon Road, Cambridge CB3 0DL, UK. E-mail: lera.miles@unep-wcmc.org
†Current address: Center for Tropical Plant Conservation, Fairchild Tropical Botanic Garden, FL, USA

ABSTRACT

Aim To analyse the conservation status of tropical dry forests at the global scale, by combining a newly developed global distribution map with spatial data describing different threats, and to identify the relative exposure of different forest areas to such threats.

Location Global assessment.

Methods We present a new global distribution map of tropical dry forest derived from the recently developed MODIS Vegetation Continuous Fields (VCF) product, which depicts percentage tree cover at a resolution of 500 m, combined with previously defined maps of biomes. This distribution map was overlaid with spatial data to estimate the exposure of tropical dry forests to a number of different threats: climate change, habitat fragmentation, fire, human population density and conversion to cropland. The extent of tropical dry forest currently protected was estimated by overlaying the forest map with a global data set of the distribution of protected areas.

Results It is estimated that 1,048,700 km^2 of tropical dry forest remains, distributed throughout the three tropical regions. More than half of the forest area (54.2%) is located within South America, the remaining area being almost equally divided between North and Central America, Africa and Eurasia, with a relatively small proportion (3.8%) occurring within Australasia and Southeast Asia. Overall, *c.* 97% of the remaining area of tropical dry forest is at risk from one or more of the threats considered, with highest percentages recorded for Eurasia. The relative exposure to different threats differed between regions: while climate change is relatively significant in the Americas, habitat fragmentation and fire affect a higher proportion of African forests, whereas agricultural conversion and human population density are most influential in Eurasia. Evidence suggests that *c.* 300,000 km^2 of tropical dry forest now coincide with some form of protected area, with 71.8% of this total being located within South America.

Main conclusions Virtually all of the tropical dry forests that remain are currently exposed to a variety of different threats, largely resulting from human activity. Taking their high biodiversity value into consideration, this indicates that tropical dry forests should be accorded high conservation priority. The results presented here could be used to identify which forest areas should be accorded highest priority for conservation action. In particular, the expansion of the global protected area network, particularly in Mesoamerica, should be given urgent consideration.

Keywords
Biodiversity, climate change, deforestation, dry forests, fire, protected areas, threat, vulnerability.

INTRODUCTION

In 1988, Janzen (1988) stated that tropical dry forests are the most threatened of all major tropical forest types. This statement was largely based on the observation that less than 2% of the tropical dry forest (TDF) in the Mesoamerican region was sufficiently intact to be considered worthy of conservation, having declined from an original area of 550,000 km^2. At that time, only 0.09% of the forests in the Mesoamerican region were accorded some degree of official protection. Janzen's statement should be seen as part of a general plea for greater conservation effort to be devoted to TDFs, written at a time when the loss of tropical rain forests was receiving greater international attention. Given that high rates of forest loss and degradation continue to be recorded in many tropical countries where dry forests are present (FAO, 2001), the issue remains acutely relevant today.

However, statements regarding the relative threats to different habitat or ecosystem types are difficult to make with precision. In recent years, substantial progress has been made in developing systematic methods for assessing the threat of extinction of individual species, most notably in support of the IUCN Red List (Mace & Lande, 1991; Reynolds & Mace, 1999; Akcakaya *et al.*, 2000; IUCN, 2001, 2003). Much less progress has been made in developing objective methods for assessing threats to ecosystems. The most widely applied approach is that developed by the World Wildlife Fund-US (WWF), which has been employed in a series of regional assessments (Dinerstein *et al.*, 1995; Ricketts *et al.*, 1999; Wikramanayake *et al.*, 2002), and to provide a global overview of the conservation status and distribution of ecoregions (Olson & Dinerstein, 1998; Olson *et al.*, 2000).

In the global assessment undertaken by WWF, 14 Major Habitat Types were differentiated, of which Tropical and Subtropical Dry Forests were one. Ten principal areas of this forest type were identified, and all were considered to be Critical/Endangered, the most threatened of the three broad categories considered (Olson *et al.*, 2000). In the regional assessments, a larger number of categories were defined, in a similar approach to the IUCN Red List categories for species, ranging from 'Extinct' to 'Relatively intact'. Four variables were used as the basis of these assessments: habitat loss, size and number of larger habitat blocks, degree of habitat fragmentation and degree of protection. Of these, the greatest weight was given to habitat loss, followed by size and number of large habitat blocks. The conservation status assessments were then modified by consideration of the possible future impact of two threats: habitat degradation and conversion. Degradation was assessed as a function of human population density, and the presence of large-scale logging concessions was used as a proxy for assessing the threat of habitat conversion (Wikramanayake *et al.*, 2002).

Other global environmental assessments provide little information specifically relating to TDF conservation status. For example, the 'hotspot' approach developed and implemented by Conservation International (Myers *et al.*, 2000) focuses on identifying areas of particular importance for biodiversity conservation on the basis of plant species endemism, and the extent of habitat loss. Although TDF areas (such as those in New Caledonia and the Caribbean) fall within the definition of 'biodiversity hotspots', the approach does not provide a comprehensive assessment of the conservation status of this forest type. The Forest Resources Assessment produced by the FAO (2001) provides statistics on the area of forest remaining in each country, as well as overall estimates of deforestation rate, but does not assess the conservation status of individual forest types. The *Conservation Atlas of Tropical Forest* series offers maps for the early 1980s–1990s, but whilst dry forests such as monsoon areas are described and sometimes mapped, there is no consistent overview of TDF (Collins *et al.*, 1991; Sayer *et al.*, 1992; Harcourt & Sayer, 1996).

The WWF assessments therefore offer one of the most comprehensive assessments of global biodiversity achieved to date, and provide support to Janzen's contention that TDFs are severely threatened in all regions where they occur. However, they do not provide sufficient detail to assess the relative conservation status of different TDF areas when considered at the global scale. As noted by the authors (Wikramanayake *et al.*, 2002), the range of threats considered is limited; important causes of habitat loss and degradation, such as fire and climate change, are not considered. In addition, as the global overview was based on a series of regional assessments, neither forest cover nor threats were assessed using globally consistent data sets. Remote sensing technology now permits such data sets to be developed and analysed.

This paper aims to provide a new global overview of the conservation status of TDFs. First, the definition of this forest type is considered, and existing sources of information on its distribution are compared. A new map of TDFs is then presented, derived from classification of a recently developed remote sensing product, which provides an improved indication of global tree cover. The threats to TDFs are then analysed by integrating the forest distribution map with spatial data sets describing the actual or potential impact of a range of threats. The results are used to identify which of the remaining areas of TDF are most at risk from environmental change and human activities, in the context of their current protection status.

METHODS

Definition of tropical dry forest

In order to assess TDF conservation status, information is required on its distribution pattern, and the rate of change in forest extent. Assessments of the extent of TDF depend critically on how this vegetation type is defined. As other authors have noted, this is a complex issue, as dry forests grade into other vegetation types such as wet forests, savannas and woodlands (Furley *et al.*, 1992). Mooney *et al.* (1995) suggest that in the simplest terms, they may be defined as forests occurring in tropical regions characterized by pronounced seasonality in rainfall distribution, resulting in several months of drought. The forests that develop under such climatic conditions share a broadly similar structure and physiognomy; many also occur on mesotrophic soils. However, as noted by Mooney *et al.* (1995), these shared characteristics are difficult to define with precision.

One of the main challenges to undertaking vegetation assessments at the global scale lies in harmonizing the many different vegetation classifications that have been developed within different regions. Blasco *et al.* (2000) provide a comparison of ten regional classification schemes developed for tropical woody vegetation, related to a common framework based on 'bioclimatic types'. This analysis highlights the difficulty of developing a common definition of TDF. Forest types (or formations *sensu* Blasco *et al.*, 2000) labelled as 'dry forest' in the regional classifications are grouped under four of the six bioclimatic types that these authors define. This suggests either that TDFs have a very broad climatic tolerance range, or that the concept is interpreted variously by different authors. Either way, this bioclimatic framework proved to be of little value for determining the distribution of TDF.

In this investigation, we adopted the global biogeographic classification presented by Olson *et al.* (2001), which was explicitly developed to support global conservation assessments. Biogeographic realms were defined by Olson *et al.* (2001) based on those presented previously by Pielou (1979) and Udvardy (1975), modified as a result of extensive literature search and expert consultation. Importantly, the classification was based primarily on biogeographic information rather than climate, and included information regarding distributions of animal species as well as plants, unlike most alternative classifications that are available (Olson *et al.*, 2001).

Olson *et al.* (2001) define tropical and subtropical dry broad-leaved forests as one of 14 biomes identified at the global scale. Tropical and subtropical grasslands, savannas and shrublands are considered together as a separate biome. In our analysis, we considered both of these biomes together as areas where TDFs might potentially occur.

Distribution of tropical dry forest

The maps presented by Olson *et al.* (2001) provide no indication of current forest cover. To develop a distribution map of TDF, we therefore masked the distribution of biomes presented by Olson *et al.* (2001) with a map of global forest cover, derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) Vegetation Continuous Fields (VCF) product (Hansen *et al.*, 2003). This depicts the percentage tree cover at a resolution of 500 m using a supervised regression tree algorithm. Training data were derived from high resolution Landsat data applied to 7 bands of MODIS data acquired between October 2000 to December 2001. The data are available through the University of Maryland Global Land Cover Facility (http://glcf.umiacs.umd.edu) and are also distributed as a MODIS land cover product.

To produce the distribution map, tropical forest was defined as those tropical grid cells with at least 40% forest cover, based on the MODIS data set, which uses a 500-m equivalent grid in geographic projection (Hansen *et al.*, 2002, Hansen *et al.*, 2003). Then, dry and seasonally dry forest was defined by further limiting this distribution to (1) cells found within the 'Tropical and subtropical dry broadleaf forest', 'Mediterranean forest, woodland and scrub', or 'Desert and xeric shrubland' biomes of the WWF ecoregions data set (Olson *et al.*, 2001); and (2) cells falling within a subset of the 'Tropical and subtropical grassland, savanna and shrub' biome (limited to areas falling within the aridity zones from the *World Atlas of Desertification* (Middleton & Thomas, 1997) to exclude this category's more humid subtypes).

This map represents the estimated maximum distribution of tropical dry and seasonally dry forest. It has not been ground-truthed, and it is particularly important to note that the definition of 'forest' is restricted to areas with 40% tree cover or greater. The 40% value corresponds to the FAO Global Forest Resources Assessment definition of closed forest (FAO, 2001).

Analysis of deforestation

The MODIS VCF tree cover product has recently been used to provide an estimate of recent tropical deforestation using a more conservative definition of dry forest (based on a threshold of 80% tree canopy – full details are provided by DeFries *et al.* (2004)). Percentage forest cover within each 500-m pixel was calculated using this threshold. Locations that have experienced loss of forest habitat over the last two decades were identified using high-resolution Landsat analyses, combined with the coarser resolution Advanced Very High Resolution Radiometer (AVHRR) Pathfinder Land data from 1982–2000 (DeFries *et al.*, 2002; Hansen & DeFries, 2004). To obtain a representative annual change value, estimates were derived for three 5-year intervals (1982–87, 1988–92, and 1992–99) by using the median change value for the interval. The difference between the first and second interval was used to represent changes in the 1980s and second and third interval to represent 1990s.

As the coarse 8-km AVHRR resolution cannot detect small patches and underestimates changes in percentage cover, a correction factor was used, based on Landsat analyses, that was as relevant as possible to each region, ranging from 1.5 in Latin America where clearing occurs in large contiguous patches to 3.7 in Africa where clearing occurs are on a much finer scale (DeFries *et al.*, 2002). The correction factors were determined by correlating forest loss derived from high resolution (30 m) Landsat data with the AVHRR estimates (DeFries *et al.*, 2002). The area of change in the AVHRR-derived percentage tree cover (the product of the difference in percentage tree cover and the pixel area) was adjusted by the correction factor to estimate changes in forest cover. Annual values for the change in percentage forest cover were used to determine the changes from 1980 to 1990, and from 1990 to 2000. Differences in deforestation between tropical moist and tropical dry forest were estimated using the 'Tropical and subtropical dry broadleaf forest' biomes (alone) defined by Olson *et al.* (2001).

Analysis of threats

Spatial data describing actual or potential threats to TDFs were obtained from a number of sources, analysed and classified as described below. All area calculations were carried out after transformation into Mollweide's projection. This is an equal-area projection, so lends greater accuracy to the analysis. In order to capture threats in the immediate area of dry forests as well as those already present within the forests, we opted to use a 10-km grid scale, coarser than that of the forest data set. This also makes some provision for geographical discrepancies and differences in scale between the global pressure data sets. Analysis was carried out separately for five major regions (following Blyth *et al.*, 2002) containing TDF: North and Central America, South America, Eurasia, Africa and Australasia/Southeast Asia.

Climate change

Projected climate changes for the 2040–69 period were derived from a set of five global climate change models running under the IS92a 'business as usual scenario'. The five general circulation models (GCMs) employed were CGCM1 (Boer *et al.*, 2000a,b; Flato *et al.*, 2000), CCSR-NIES (Abe-Ouchi *et al.*, 1996; Emori *et al.*, 1999), CSIRO-Mk2b (Hirst *et al.*, 1996, 2000), GFDL-R15 (Manabe *et al.*, 1991; Stouffer *et al.*, 1994; Manabe & Stouffer, 1996) and HAD-CM2 (Cullen, 1993). Mean monthly temperature and precipitation anomalies (12 values for each 30-year period) with respect to 1961–90 climate were obtained for each GCM from the IPCC Data Distribution Centre (http://ipcc-ddc.cru.uea.ac.uk). These values had been computed by comparing the 1961–90 model climate with model output over a 30-year period centred on 2050, following Carter *et al.* (1999).

Mean annual values were obtained by summing (precipitation) or averaging (temperature) the 12 monthly values for each variable. The mean values were spatially interpolated using the Tension Spline function in ArcInfo to produce a summary map of temperature and precipitation. 'Severe climate change' was defined as either a temperature increase of at least 2.5 °C or a precipitation decrease of at least 50 mm year^{-1} by 2055, averaged for the five GCMs.

Forest fragmentation

A global data set describing forest spatial integrity (a measure of the degree of forest fragmentation) was created following the method of Kapos *et al.* (2000), using the same forest definition and data set as above. Equidistant Conic continental projections were used for each of the five regions to improve the local accuracy of the distance calculations required by the metric. Forest patch size, local forest patch density ('edge', *sensu* Kapos *et al.*, 2000) and patch connectivity were defined and scaled using parameters relevant to an animal with large territory size as follows. Patch size was classified on a linear scale from < 10 to > 300 km^2. Local forest patch density was defined as the percentage of forested cells within a 5 km radius of the target grid cell, including that cell. Connectivity depended upon the definition of core areas of forest. If a cell did not fall into a patch that included a forest cell defined as core, or if a cell was more than 18 km from the nearest core cell, its connectivity was defined as 0. Otherwise, connectivity was defined as the distance of the minimum path through forested cells to a core cell. Core cells were those falling into contiguous groups of more than 100 km^2 area, in which each cell has local forest density > 60%.

Each of the three indices was scaled to values between 1 and 100. A single combined index was calculated according to the following formula (Kapos *et al.*, 2000): Spatial Integrity = (0.25 × Patch Size) + (0.25 × Local Patch Density) + (0.5 × Connectivity). Cells with low values of the index are subject to high levels of fragmentation. 'Severe fragmentation' was defined as an index value of ≤ 20.

Fire

An assessment of global fire occurrence was derived from the ATSR Night-time Hotspots data set produced by the ATSR World Fire Atlas project (European Space Agency – ESA/ESRIN, Frascati, Italy), which provides a count of apparent fires detected from January 1998 to December 2000 by the ATSR satellite. The satellite's overpass time at night is around 22:30 local time. The current analysis employed the data from 'algorithm 2', for which the cut-off point for estimating that a fire was present was 'Hotspot if: 3.7 μm > 308 °K (*c.* 35 °C)'. This band is very sensitive to high temperature emitting bodies (around 1000 °K). The data set is validated. 'Hotspots' for all years combined were converted into a point map. All those 10-km cells that had hosted a hotspot over the 3-year period were assumed to be at a high risk of fire.

Conversion to agriculture

The threat of conversion to agricultural cropland was assessed using an FAO map of agrosuitability for rainfed crops ('maximizing technology mix'; Fischer *et al.*, 2000, 2001). The 5′ resolution data set is based on crop modelling and environmental matching procedures. These were used to identify crop-specific limitations of prevailing climate, soil and terrain resources, under assumed levels of inputs and management conditions. Yield calculations for various crops were then based on climate and edaphic characteristics from various existing digital coverages, and used to determine the suitability of land for agricultural production, classified into categories of 'very suitable', 'suitable', 'moderately suitable' or 'marginally suitable' (Fischer *et al.*, 2000, 2001). We assumed that forest falling into a 10-km cell identified as any of the first three categories was at high risk of agricultural conversion.

Human population

The Gridded Population of the World data set (GPW version 2, 1995) available from CIESIN (http://www.ciesin.org/datasets/gpw/globldem.doc.html) was used to assess human population density. We assumed that forest falling into a 10-km cell identified as containing > 2500 individuals was at high risk from human activity. The data date from 1994.

Generation of threat statistics

The high risk categories from each of the pressures were used to generate binary maps. A GIS overlay analysis was then carried out to identify the number of 'high risk' threats that each cell from the TDF map is subject to. Statistics were then generated describing the area of forest affected by each threat within each geographical region. For these calculations, the definition of regions followed Blyth *et al.* (2002). Note that according to this definition, 'Eurasia' includes all of continental Asia, but Southeast Asia/Australasia includes all the Southeast Asian island states. The countries of Indochina (including Thailand, Vietnam, Laos and Cambodia) are therefore considered as part of Eurasia rather than Southeast Asia.

Protected area data

Data were derived from the World Database on Protected Areas, which is managed by UNEP-WCMC in association with the IUCN World Commission on Protected Areas (WCPA). The data base was accessed in August 2002, and all protected areas in IUCN categories I–IV were included, plus other national sites with spatial coordinates in the data set. Data were superimposed over the distribution map of TDF to generate regional statistics of the extent of forest incorporated within a protected area.

RESULTS

Distribution of tropical dry forest

The most striking feature of the TDF distribution map is the fact that the two most extensive contiguous areas that remain are both located in South America, one in north-eastern Brazil, and the other in south-eastern Bolivia, Paraguay and northern Argentina (Fig. 1). Other notable concentrations of TDF occur within the Yucatan peninsula of Mexico, northern Venezuela and Colombia, and in Central Indochina (Thailand, Vietnam, Laos and Cambodia). In most other areas where dry forests occur, they tend to display a rather scattered or fragmented distribution, often over extensive areas. Diffuse concentrations of dry forest occur along the Pacific coast of Mexico, eastern India and Sri Lanka, in the island chain east of Java, and in northern Australia. In Africa, TDFs are distributed over an extensive geographical range, but nowhere form large continuous areas. The two main centres of distribution are located in western Ethiopia, southern Sudan and the Central African Republic, and in Zambia, Zimbabwe and Mozambique. Scattered dry forests also remain in western Madagascar, and in West Africa (principally Mali).

This same pattern is reflected in the analysis of the relative distribution of this forest type among different regions, which

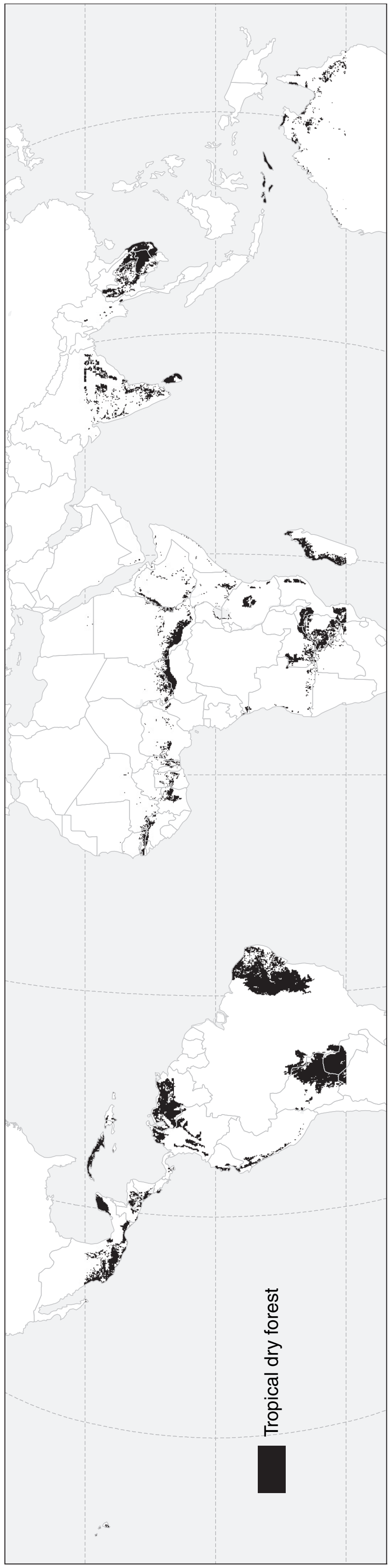

Figure 1 Global distribution of tropical dry forest in the year 2000, displayed as 10-km cells containing this forest type (including plantations in tropical dry forest areas). Based on biogeographic realms from Olson *et al.* (2001) masked with MODIS 500-m resolution forest cover data set (Hansen *et al.*, 2003), with forest canopy cover > 40%. For details, see text. Robinson projection.

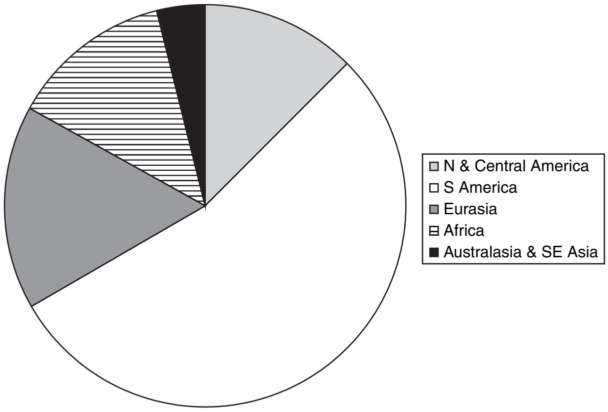

Figure 2 Distribution of tropical dry forest among geographical regions in the year 2000. For definitions of regions, see text.

indicates that more than half (54.2%) of the remaining dry forests are located within South America (Fig. 2). The remaining area of dry forest is almost equally divided between North and Central America (12.5%), Africa (13.1%) and Eurasia (16.4%), with a relatively small proportion occurring within Australasia and (insular) Southeast Asia (3.8%). Based on this map, the total estimated area of remaining TDF is around 1,048,700 km^2.

Analysis of deforestation

The percentage of forested area in 2001, relative to total area of habitat delineated by Olson *et al.* (2000), varies from *c.* 16% in dry forests of South and Southeast Asia to more than 40% in the case of Latin America. Of all the regions considered, dry forests of Latin America experienced the greatest decreases between 1980 and 2000 in percentage area forested (relative to total habitat area), with an estimated figure of 12% (0.22×10^6 km^2 decrease). The corresponding figure for Asia was relatively low, at *c.* 2%. With respect to Africa, deforestation rates were also relatively low, with the exception of Madagascar, where a loss of 18% (0.06×10^6 km^2) was recorded for this period (Fig. 3).

Analysis of threats

Climate change

The analysis of risk of climate change highlighted a striking difference among regions. Specifically, a far higher proportion of dry forest areas was at risk of severe climate change in the Americas than in the other regions, with percentages of 39.8% and 37.0% recorded for North and Central America, and for South America, respectively. In each of the other regions, the

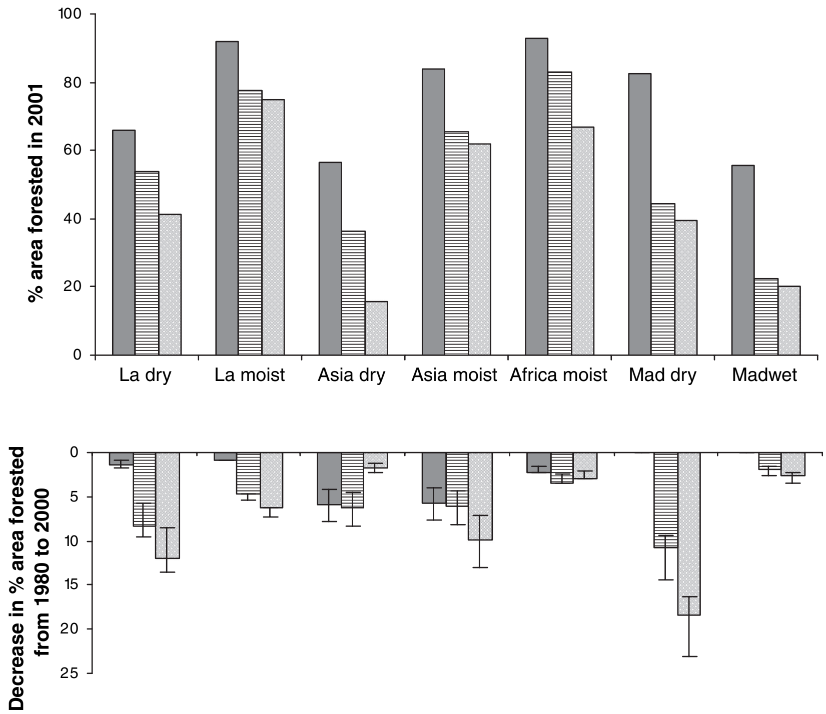

Figure 3 Estimated percentage area forested in the year 2001 relative to total area of forest habitat (top) and estimated decreases in percentage forest area from 1980 to 2000 relative to total area (bottom) within the administrative boundaries of the protected areas (dark grey), within the 50-km buffer surrounding the protected areas (striped) and total area (dotted). Abbreviations, with total habitat area as delineated by Olson *et al.* (2000) in 10^6 km^2 given in parentheses, are: LA DRY = Latin American Dry Forests (1.8), LA MOIST = Latin American Moist Forests (9.2), ASIA DRY = South and Southeast Asia Dry Forests (3.7), ASIA MOIST = South and Southeast Asia Moist Forests (6.0), AFRICA MOIST = African Moist Forests (3.3), MAD DRY = Madagascar Dry Forests (0.3), MAD MOIST = Madagascar Moist Forests (0.3) (after DeFries *et al.*, 2004). Error bars represent the range of estimates for decrease in forest cover based on correction factors for calibrating AVHRR- and Landsat-derived estimates (see DeFries *et al.*, 2002).

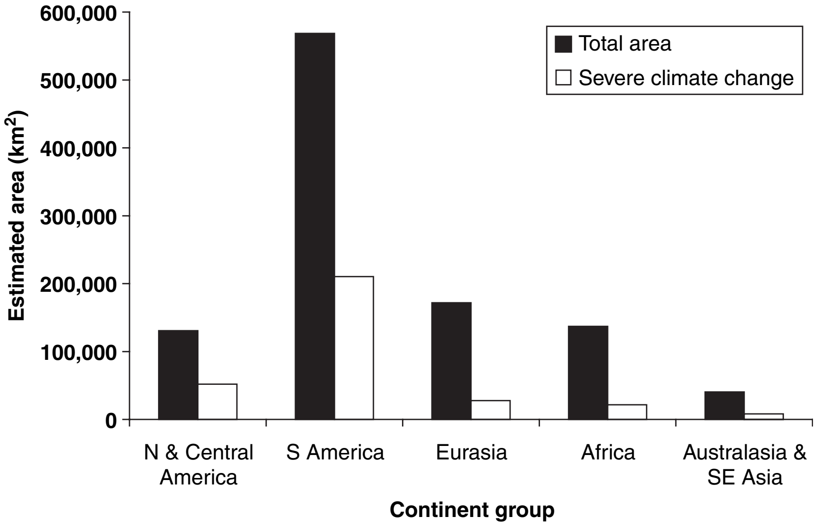

Figure 4 Estimated distribution of tropical dry forest at risk of serious climate change (2040–69). For details of methods of calculation, see text.

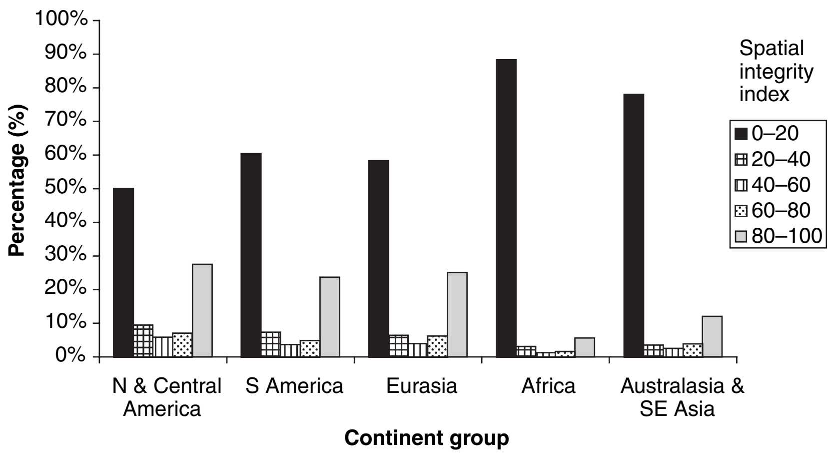

Figure 5 Estimated forest spatial integrity for 10-km cells containing tropical dry forest, providing an indication of the extent of forest fragmentation in the year 2000. For details of methods of calculation, see text.

percentage of dry forest at risk of severe change was < 20% (Fig. 4). These results reflect the large decrease in precipitation envisaged in many parts of tropical America by current models of climatic change.

This simple analysis focuses on the risk to existing areas of forest. With this projected decrease in precipitation, it is likely that new areas would become climatically suitable for dry forest; but considerable further analysis would be necessary to investigate whether, and within what timescale, dry forest species could colonize those new potential distribution areas.

Forest fragmentation

The analysis of forest fragmentation produced an unusual distribution among the different classes of forest spatial integrity index (Fig. 5). Each region displayed a bimodal distribution, with peaks in the 0–20 and 80–100 class intervals. Other values of the index were less well represented. The high frequency of the 0–20 class, in every region, was particularly noteworthy. These results imply that dry forests tend to occur either as relatively intact blocks of habitat, or as highly fragmented patches. In every region, the most highly fragmented values of the index (0–20) were the most frequently encountered, representing between 49.9% (North and Central America) and 88.2% (Africa) of total dry forest area. The percentage area of highly fragmented forest was also relatively high (77.9%) in Southeast Asia and Australasia, compared to other regions. These results suggest that at the 500-m grid cell scale, TDFs tend to be highly fragmented in all regions where they occur.

Fire

The occurrence of fire in TDF areas differed relatively little between geographic regions (Fig. 6), with values ranging between 17.4% (Eurasia) to 26.9% (Africa) of forest areas affected by fire. Fire is a natural occurrence in dry forests, but where fire frequency increases so that trees cannot regenerate, forest cover will decline. Given that these data were collected within a period of only 3 years, fire appears to be a widespread and significant potential threat to dry forests, affecting some 1,106,300 km^2 of dry forest area during this period. Variation was also encountered within regions, with the forests of Mexico and Central Indochina experiencing relatively high occurrence of fire. To put this risk in context, it would be useful to compare these data with the background fire

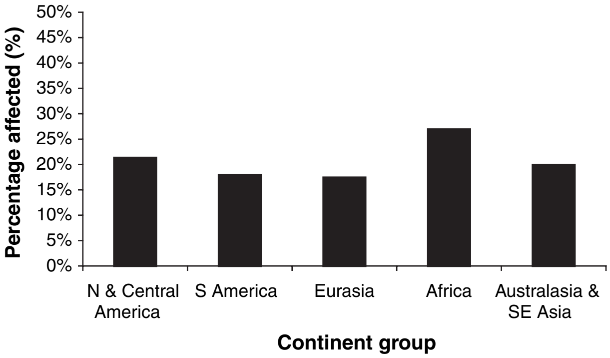

Figure 6 Estimated percentage of 10-km cells containing tropical dry forest to have experienced fire, 1998–2000. For details of methods of calculation, see text.

frequency in a pre-industrial world, but as far as we can ascertain, such a global map is not available.

Conversion to agriculture

Pronounced variation between regions was identified with respect to the areas of dry forest at high risk of agricultural conversion (Fig. 7). Estimates of forest areas with high suitability for cultivation of rain-fed crops ranged from 5.5% (Southeast Asia and Australasia) to 20.2% (Eurasia), an almost four-fold difference. When all four categories of suitability for crop cultivation were considered, total values of more than 60% forest area were recorded for South America, Eurasia and Africa, suggesting that agricultural conversion represents a substantial threat in these regions. In contrast, combined values for North and Central America and for Southeast Asia and Australasia were substantially lower, at 41.4% and 33.9% respectively.

Human population

Again, human population density displayed pronounced variation among regions, the most striking feature being the relatively low population density in dry forest areas of Southeast Asia and Australasia (Fig. 8). In terms of the percentage forest area with the highest population density category (> 2500 individuals 10 km^{-2}), Eurasia and North and Central America displayed substantially higher values than the other regions considered, with values of 81.9% and 63.2% respectively. This reflects the particularly high human populations densities recorded in Mexico, eastern India and Central Indochina. In contrast, only 17.4% of African TDFs coincide with areas of high population density.

Integrated threats

Overall, only 3.3% of the remaining global area of TDF is not currently at high risk from one or more of the threats considered in this analysis. For any individual region, this figure does not rise above 5%. These results therefore suggest that the vast majority of TDF, in all regions, is under at least a degree of threat. In terms of the forest areas subjected to all five threats considered, percentage values were relatively low, with maximum values of 2.92% and 1.13% recorded for Eurasia and North and Central America, respectively (Fig. 9). However, substantial areas of TDF are subjected to three or more threats (Fig. 10), values ranging from 31.7% in the case of South America, to 59.2% in the case of Eurasia. The percentage of forest subjected to two or more threats was > 95% for each of the regions considered.

Protected areas

The data describing the area of TDF designated as protected illustrate some pronounced differences between regions (Fig. 11). Values of the percentage of dry forest that is protected range between 5.7% for North and Central America, to 37.8% for South America. The percentage of dry forests protected in Southeast Asia is also relatively low, at 14.2%. In total, an estimated TDF area of 299,100 km^2 is now designated as protected world-wide, with 71.8% of this total being located within South America.

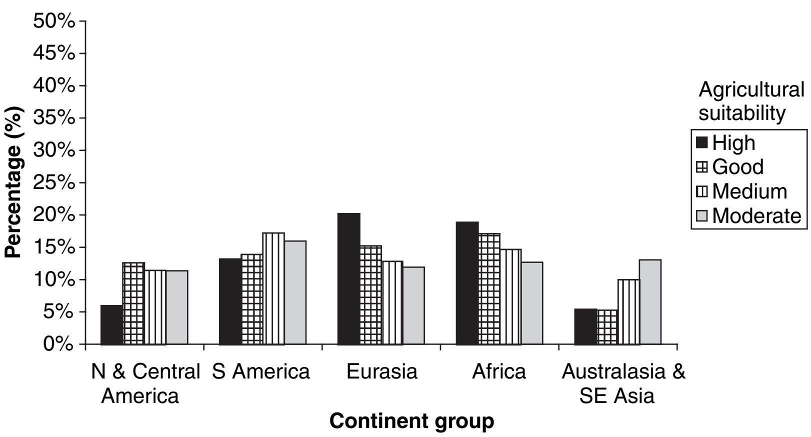

Figure 7 Estimated percentage of 10-km cells containing tropical dry forest with greater than marginal suitability for rain-fed crops in the year 2000. For details of methods of calculation, see text.

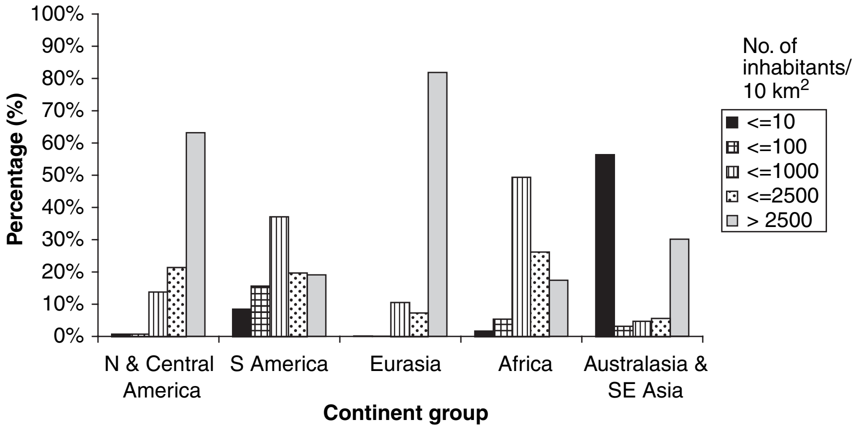

Figure 8 Estimated human population in 1994 for 10-km cells containing tropical dry forest in 2000. For details of methods of calculation, see text.

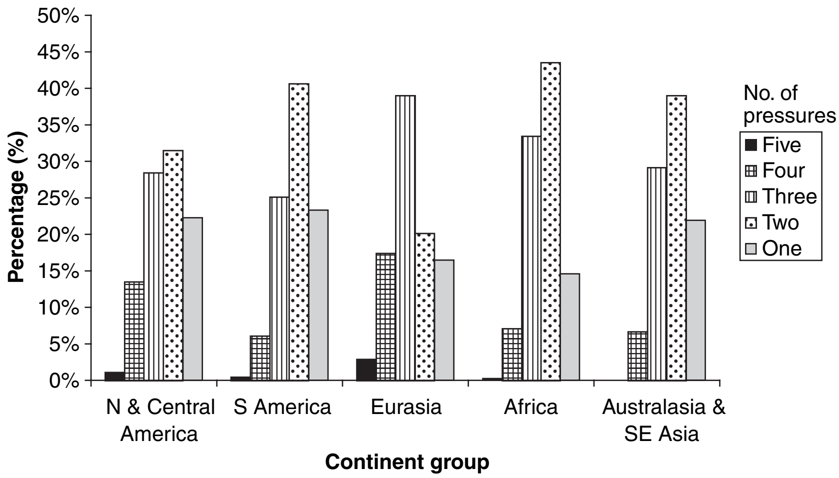

Figure 9 Estimated percentage of 10-km cells containing tropical dry forest subject to multiple possible pressures, including future climate change. For details of methods of calculation including dates, see text.

DISCUSSION

The MODIS tree cover product employed here represents a significant advance over previous attempts to map global forest cover using other sources of remote sensing data, such as AVHRR, because of its higher spatial resolution (Hansen *et al.*, 2003). Most previous global maps of the distribution of TDF were either based on climate, or produced by compiling regional surveys. The global map of ecological zones presented as part of the most recent Global Forest Resources Assessment (FAO, 2001) includes TDF as a category, but is based on climate alone (i.e. Köppen–Trewartha climatic types) and includes no assessment of current forest cover; the map therefore presents potential rather than actual forest cover. The first global map of forest cover based on remote sensing data, produced by UNEP-WCMC (Groombridge & Jenkins, 2000), was compiled from a variety of different national and international sources rather than a globally consistent data set; in addition, TDF was not differentiated as a distinct vegetation type.

A global land cover map was produced by the University of Maryland Global Land Cover Facility based on AVHRR Pathfinder Land (PAL) data at a resolution of 1 km, trained using Landsat data (Hansen *et al.*, 2000). However, TDFs were again not differentiated as a specific land-cover type; instead, a more general classification was adopted, including categories such as deciduous broadleaf forest, mixed forest, woodland, and wooded grassland. An attempt was later made to reclassify this map according to forest ecosystem types, rather than land-cover types (Groombridge & Jenkins, 2002, p. 107). Comparison of this map with that provided here indicates a number of substantial differences; for example the area of TDF in South America is far larger on the current map, whereas the dry forest area in Africa is significantly smaller. These differences may be attributed to the inclusion of 'sparse trees and parkland' as a separate category in the map presented by Groombridge & Jenkins (2002), and the fact that the MODIS data employed here are at a much higher resolution than the AVHRR data on which the earlier map was based.

Other vegetation mapping initiatives are currently in progress that may provide improved assessments of tropical forest distribution in the future. For example, the Joint Research Centre (JRC) of the European Commission is

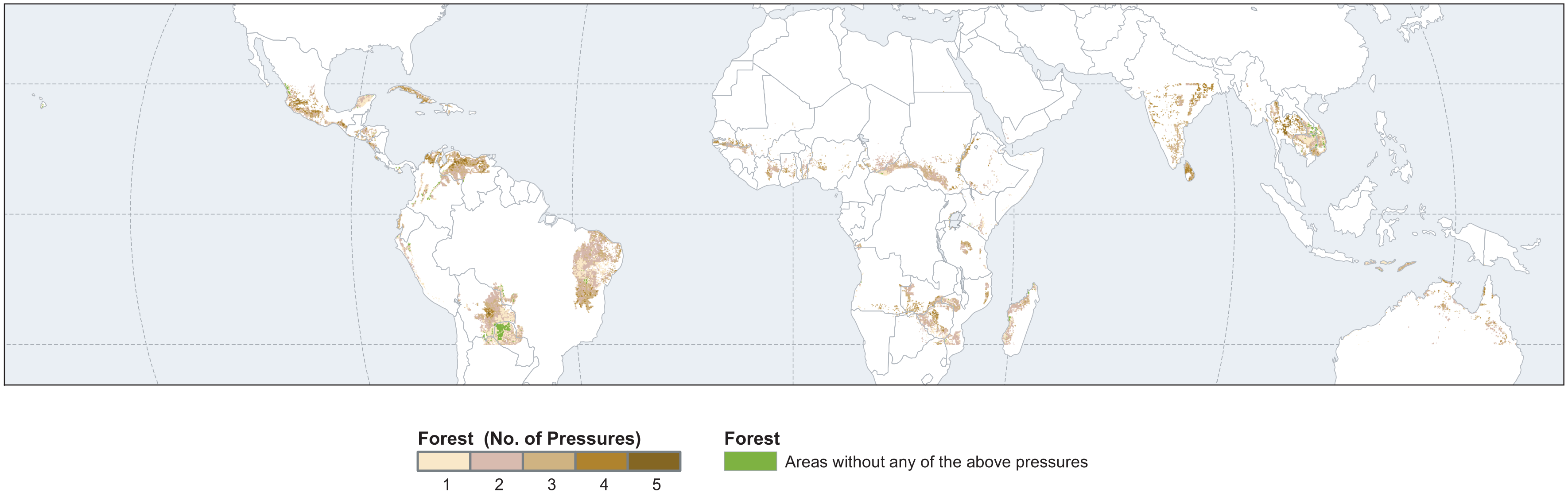

Figure 10 Global distribution of tropical dry forest illustrating the spatial variation in exposure to different threats, including future climate change. For details of methods of calculation, including dates, see text. Robinson projection.

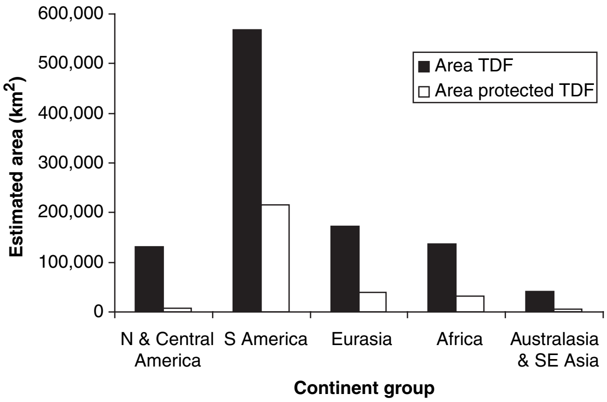

Figure 11 Estimated designated protected area (2002) coinciding with tropical dry forest (2000), compared to total tropical dry forest. For details of methods of calculation, see text.

currently developing a harmonized global land cover data base, under the Global Land Cover 2000 Project (GLC 2000). The GLC 2000 (Joint Research Centre, 2003) is using the VEGA 2000 data set acquired by the SPOT 4 satellite. The current version of this map provides an indication of the distribution of closed and open deciduous tree cover, as well as evergreen tree cover, but does not attempt to define different forest types. As TDFs may either be deciduous or evergreen, and either open- or closed-canopy (Mooney *et al.*, 1995), this classification alone is likely to have limited value for assessing the status of this forest type. This highlights the limitations of land cover classifications for undertaking conservation assessments based on ecosystems or habitat types.

Comparison of the TDF map presented here with regional assessments, based on expert knowledge, potentially provides a more useful form of validation than comparison with global land cover maps. The distribution of TDF in Mexico and Central America illustrated by Murphy & Lugo (1995), based on a range of sources, accords closely with that presented here, if the semi-evergreen seasonal forests of the Yucatan peninsula are considered as dry forest. Murphy & Lugo (1995) do not provide a comprehensive assessment of TDF distribution among the islands of the Caribbean; the current analysis suggests that the most extensive areas that remain are located in Cuba, Haiti and the Dominican Republic, in close agreement with the map presented by Gentry (1995). The current map suggests that three substantial areas of TDF remain in South America; in north-eastern Brazil (caatinga) (Sampaio, 1995), Venezuela and northern Colombia, and south-eastern Bolivia, Paraguay and northern Argentina, with limited areas remaining in Ecuador and Peru. Again, the current map accords closely with those presented by Gentry (1995) and Pennington *et al.* (2000).

Menaut *et al.* (1995) provide a valuable account of dry forests in Africa, including areas with a discontinuous tree canopy, termed 'woodlands'. The current map generally agrees with that presented by Menaut *et al.* (1995), indicating two main areas: an elongate area situated between 6° and 13° N in the northern hemisphere, and a more extensive area between 5° and 20° S in the southern hemisphere. Overall, however, the extent of dry forest indicated here is substantially less than that suggested by Menaut *et al.* (1995), which indicates potential rather than actual vegetation cover. In addition, some areas defined as dry forest in this investigation are classified as 'tree/shrub savannas' by Menaut *et al.* (1995). With respect to Asia, the current assessment highlights extensive areas of dry forests in southern and eastern India and Sri Lanka, as indicated by Blasco *et al.* (1996). Another extensive area is located within Central Indochina (Thailand, Vietnam, Laos and Cambodia), coinciding with the distribution of dry deciduous woodlands as indicated by Blasco *et al.* (1996) and Rundel & Boonpragob (1995). Dry forest areas are also indicated in the islands east of Java, defined as the Nusu Tenggara ecoregion by Olson *et al.* (2000), as well as northern Australia.

As with any map, the distribution of TDF presented here should be interpreted with caution; clearly the results are dependent on the assumptions and data on which the classification was based. The areal and distribution estimates will be affected by errors of commission and omission. Very small patches of forest, such as those occurring within savanna or evergreen forest in Latin America, will not be captured by the analysis; similarly, some cells that are included will not be fully forested. Any errors in the classification of the satellite data will be carried through into our analysis, and plantation forests are not distinguished from natural forest, so will contribute to an overestimation of tropical dry forest area.

As indicated above, the map is generally consistent with regionally based assessments, and has the additional advantage of being based on globally consistent data. The results highlight the importance of South America as the region with the largest remaining area of this forest type, but also indicate that conservation of TDFs is an issue relevant to all tropical regions.

It is now widely recognized that the assessment of threats to biodiversity is a key component of effective conservation strategies (Salafsky *et al.*, 2002). However, progress in developing objective methods of assessing threats to habitats or ecosystems has been slow. Wilson *et al.* (2005) provide a recent review of relevant approaches, through consideration of the concept of vulnerability, which may be defined as the likelihood or imminence of biodiversity loss to current or impending threatening processes (Pressey *et al.*, 1996). From a consideration of six different methods, Wilson *et al.* (2005) conclude that spatially explicit statistical or process-based modelling approaches offer the most quantitative and objective means of assessing the exposure of areas to threatening processes.

The approach adopted here to assessing exposure to threats, while analytically simple, has the advantage of being based on quantitative data rather than subjective scoring, and considers a larger number of threats than previous conservation assessments undertaken at the global scale (Olson *et al.*, 2000). This study represents the first attempt to apply such a method explicitly to the assessment of TDFs, but employs an approach previously applied to an assessment of montane environments (Blyth *et al.*, 2002). Clearly, the current assessment should be viewed as preliminary; future assessments might usefully consider additional threats such as browsing by livestock and fuelwood extraction that were not considered here despite their importance as threats to TDF (Olson *et al.*, 2000), because of the lack of suitable global data sets. Future analysis might also benefit from the application of probabilistic spatial modelling approaches, as advocated by Wilson *et al.* (2005), and incorporate assessments of the relative severity of and biotic response to different threats, as well as interactions between them. In addition, it should be noted that floristic differences often occur between areas of TDF on a local scale, and therefore information on patterns of diversity and endemicity should be incorporated within any assessments aiming at conservation prioritization.

The accuracy, characteristics and source of the data sets employed here for the threat analysis should also be considered when interpreting the results. For example, the climate change data are based on models rather than observations; gridded values are developed from models operating at coarse scales, and therefore their interpretation at finer scales should be very tentative. Fine scale processes are not represented in detail in global climate models. The accuracy of the fire data is likely to have been influenced by cloud presence, atmospheric effects and bidirectionality of emissivity, which are difficult to evaluate with precision. Only night-time fires were detected, so fires extinguished during the day are likely to have been omitted, and the data do not provide an indication of the intensity of the fires that occurred. As fire frequency is not assessed, this study does not distinguish areas where fires occur at 'natural' levels from areas where fire is a cause of forest degradation or loss. The agricultural suitability data set refers only to rain-fed agriculture, and excludes pastures, agroforestry and crops requiring irrigation, each of which may be established following conversion of dry forest. In the case of habitat fragmentation, a variety of different methods are available, which vary with respect to the precise calculations employed (Kapos *et al.*, 2000; Riitters *et al.*, 2000). Here we used human population density as a proxy for other anthropogenic impacts on forests, following Wikramanayake *et al.* (2002), but clearly this is a gross oversimplification as it does not take into account consumption patterns.

Despite such caveats, the current analysis provides a first overview of the extent to which TDF areas are at risk from human activities. The results emphasize that TDFs remain an urgent conservation priority. The results of the deforestation analysis (DeFries *et al.*, 2004) provide support for Janzen's (1988) original contention that dry forests are the most threatened major tropical forest type, at least in South America and Africa, given the higher deforestation rates recorded in these regions for dry forest compared to tropical moist forest.

Some 97% of the remaining area of TDF is currently exposed to a high level of one or more of the threats considered here (excluding deforestation, which was treated separately). This compares with a value of 56% for temperate rain forests derived using precisely the same data sets and methods of analysis (L. Miles *et al.*, unpublished data). In terms of the proportion of TDF area affected by three or more threats, southern Eurasia emerges as the most threatened of the regions considered here, in north-eastern India, Sri Lanka and Thailand in particular. Other areas currently exposed to multiple threats, and which may therefore be considered as conservation priorities, include in Africa, those of Zimbabwe and Zambia, scattered locations throughout West Africa, and the forests situated along the border between Sudan and Ethiopia. In the Americas, extensive areas of highly vulnerable TDF are located in Mexico, Cuba, Venezuela, northern Colombia, central Bolivia and eastern Brazil. Of the ten tropical and subtropical dry forest ecoregions identified by Olson *et al.* (2000) as priorities for conservation, the results of the present analysis suggest that the Indochina, Chhota-Nagpur (India), Mexico and Chiquitano (Bolivia) Dry Forest Ecoregions are those that are most threatened. However, in terms of recent deforestation, the Madagascar dry forest ecoregion is also clearly highly threatened.

Little TDF was afforded some degree of protection in 1988 (0.09% in Mesoamerica, Janzen, 1988). In this respect, the current analysis provides some evidence of improvement, as > 5% of Mesoamerican dry forests are now protected. However, the area protected within Central America is still disproportionately low compared to other regions. We estimate that around 200,000 ha of TDF are now designated as protected within South America, representing 37.8% of the total area of this forest type occurring within the region. These data should also be interpreted with caution, as the basis of the calculation was to identify grid cells containing protected areas that also contain TDF, rather than that identifying the precise area of TDF that is definitely protected. It should be noted that the different areas of dry forest in South America are floristically very different, and in some areas with relatively high endemism (such as the inter-Andean valleys of Peru or Bolivia), protection is entirely absent. Also, designation of a protected area does not ensure that conservation is necessarily effective.

CONCLUSIONS

The global distribution map of TDFs presented here represents the first attempt to map this forest type using data derived from a global remote sensing survey. Dry tropical forests are subject to multiple pressures, often simultaneously. These results indicate that there is a substantial need for expanding the protected area network to include TDF areas, particularly in South, Central and North America. Expansion of the global network of protected areas remains a key priority if the distinctive biodiversity of TDFs is to be conserved effectively in the future. Those forest areas most at risk from human activity, such as those identified in this analysis, as well as those of highest biodiversity value, should be accorded highest priority for future conservation action.

ACKNOWLEDGEMENTS

Funding for this research was provided by the European Commission as part of the 'Biodiversity conservation, restoration and sustainable use in fragmented forest landscapes (BIOCORES)' project, INCO Contract ICA4-CT-2001-10095. Financial support was also provided by DEFRA, UK, as part of the 'Forests at Risk' project. Fire data were provided by the ATSR World Fire Atlas, European Space Agency – ESA/ESRIN, Frascati, Italy. The other public domain global data sets used here are gratefully acknowledged and sourced as referenced.

REFERENCES

Abe-Ouchi, A., Yamanaka, Y. & Kimoto, M. (1996) *Outline of CCSR-98 coupled atmosphere and ocean model and experiment*. Internal report, Centre for Climate Systems Research, University of Tokyo, Tokyo, Japan.

Akcakaya, H.R., Ferson, S., Burgman, M.A., Keith, D.A., Mace, G.M. & Todd, C. (2000) Making consistent IUCN classifications under uncertainty. *Conservation Biology*, **14,** 1001–1013.

Blasco, F., Bellan, M.F. & Aizpuru, M. (1996) A vegetation map of tropical continental Asia at scale 1 : 5 million. *Journal of Vegetation Science*, **7,** 623–634.

Blasco, F., Whitmore, T.C. & Gers, C. (2000) A framework for the worldwide comparison of tropical woody vegetation types. *Biological Conservation*, **95,** 175–189.

Blyth, S., Groombridge, B., Lysenko, I., Miles, L. & Newton, A.C. (2002) *Mountain watch. Environmental change and sustainable development in mountains*. UNEP-WCMC, Cambridge.

Boer, G.J., Flato, G.M. & Ramsden, D. (2000a) A transient climate change simulation with greenhouse gas and aerosol forcing: projected climate to the twenty-first century. *Climate Dynamics*, **16,** 427–450.

Boer, G.J., Flato, G.M., Reader, M.C. & Ramsden, D. (2000b) A transient climate change simulation with greenhouse gas and aerosol forcing: experimental design and comparison with the instrumental record for the twentieth century. *Climate Dynamics*, **16,** 405–425.

Carter, T.R., Hulme, M. & Lal, M. (1999) *Guidelines on the use of scenario data for climate impact and adaptation assessment v1*. Intergovernmental Panel on Climate Change, Task Group on Scenarios for Climate Impact Assessment, IPCC, Geneva.

Collins, N.M., Sayer, J.A. & Whitmore, T.C. (eds) (1991) *The conservation atlas of tropical forests: Asia and the Pacific*. Macmillan, London.

Cullen, M.J.P. (1993) The unified forecast/climate model. *The Meteorological Magazine*, **122,** 81–95.

DeFries, R., Houghton, R.A., Hansen, M., Field, C., Skole, D.L. & Townshend, J. (2002) Carbon emissions from tropical deforestation and regrowth based on satellite observations for the 1980s and 90s. *Proceedings of the National Academy of Sciences USA*, **99,** 14256–14261.

DeFries, R., Hansen, A., Newton, A.C. & Hansen, M.C. (2004) Increasing isolation of protected areas in tropical forests over the past twenty years. *Ecological Applications*, **15,** 19–26.

Dinerstein, E., Olson, D.J., Graham, D.M., Webster, A.L., Primm, S.A., Bookbinder, M.P. & Ledec, G. (1995) *A conservation assessment of the terrestrial ecoregions of Latin America and the Caribbean*. The World Bank, Washington, DC, USA.

Emori, S., Nosawa, S., Abe-Ouchi, A., Numaguti, A., Kimoto, M. & Nakajima, J.N. (1999) Coupled ocean–atmosphere model experiments of future climate change with an explicit representation of sulfate aerosol scattering. *Journal of the Meteorological Society of Japan*, **77,** 1299–1307.

FAO (2001) *Global forest resources assessment*. Main report. FAO Forestry Paper 140. Food and Agriculture Organization of the United Nations, Rome, Italy.

Fischer, G., van Velthuizen, H., Nachtergaele, F.O. & Medow, S. (2000) *Global Agro-Ecological Zoning (GAEZ) 2000 CD-ROM*. FAO/IIASA, Rome/Laxenburg, Italy/Austria.

Fischer, G., van Velthuizen, H.T. & Shah, M. (2001) *Global agro-ecological assessment for agriculture in the 21st century: methodology and results*. IIASA Research Report RR-02–02. International Institute for Applied Systems Analysis, Laxenburg, Austria.

Flato, G.M., Boer, G.J., Lee, W.G., McFarlane, N.A., Ramsden, D., Reader, M.C. & Weaver, A.J. (2000) The Canadian Centre for Climate Modelling and Analysis global coupled model and its climate. *Climate Dynamics*, **16,** 451–467.

Furley, P.A., Proctor, J. & Ratter, J.A. (eds) (1992) *Nature and dynamics of forest–savanna boundaries*. Chapman and Hall, London.

Gentry, A.H. (1995) Diversity and floristic composition of neotropical dry forests. *Seasonally dry tropical forests* (ed. by S.H. Bullock, H.A. Mooney and E. Medina), pp. 146–194. Cambridge University Press, Cambridge.

Groombridge, B. & Jenkins, M. (2000) *Global biodiversity: Earth's living resources in the 21st century*. UNEP World Conservation Monitoring Centre, Cambridge.

Groombridge, B. & Jenkins, M. (2002) *World atlas of biodiversity*. Prepared at UNEP World Conservation Monitoring Centre. California University Press, Berkeley, Los Angeles, CA.

Hansen, M. & DeFries, R. (2004) Detecting long term forest change using continuous fields of tree cover maps from 8 km AVHRR data for the years 1982–1999. *Ecosystems*, **7,** 695–716.

Hansen, M., DeFries, R., Townshend, J.R.G. & Sohlberg, R. (2000) Global land cover classification at 1 km resolution using a decision tree classifier. *International Journal of Remote Sensing*, **21,** 1331–1365.

Hansen, M., DeFries, R., Townshend, J.R.G., Sohlberg, R., Dimiceli, C. & Carroll, M. (2002) Towards an operational MODIS continuous field of percent tree cover algorithm: examples using AVHRR and MODIS data. *Remote Sensing of the Environment*, **83,** 303–319.

Hansen, M.C., DeFries, R.S., Townshend, J.R.G., Carroll, M., Dimiceli, C. & Sohlberg, R.A. (2003) Global percent tree cover at a spatial resolution of 500 meters: first results of the MODIS Vegetation Continuous Fields algorithm. *Earth Interactions*, **7,** 1–15.

Harcourt, C.S. & Sayer, J.A. (eds) (1996) *The conservation atlas of tropical forests: the Americas*. Simon & Schuster, London.

Hirst, A.C., Gordon, H.B. & O'Farrell, S.P. (1996) Global warming in a coupled climate model including oceanic eddy-induced advection. *Geophysical Research Letters*, **23,** 3361–3364.

Hirst, A.C., O'Farrell, S.P. & Gordon, H.B. (2000) Comparison of a coupled ocean–atmosphere model with and without oceanic eddy-induced advection. Part I: Ocean spinup and control integrations. *Journal of Climate*, **13,** 139–163.

IUCN (2001) *IUCN Red List categories and criteria: Version 3.1*. IUCN Species Survival Commission. IUCN, Gland and Cambridge.

IUCN (2003) *Guidelines for application of IUCN Red List criteria at regional levels: Version 3.0*. IUCN Species Survival Commission. IUCN, Gland and Cambridge.

Janzen, D. (1988) Tropical dry forests. The most endangered major tropical ecosystem. *Biodiversity* (ed. by E.O. Wilson), pp. 130–137. National Academy of Sciences/Smithsonian Institution, Washington DC.

Joint Research Centre (2003) *Global Land Cover 2000 database*. European Commission, Joint Research Centre. http://www-gvm.jrc.it/glc2000/ Accessed 23 March 2005.

Kapos, V., Lysenko, I. & Lesslie, R.G. (2000) *Assessing forest integrity and naturalness in relation to biodiversity*. FAO/UNEP-WCMC, Cambridge.

Mace, G.M. & Lande, R. (1991) Assessing extinction threats: towards a reassessment of IUCN endangered species categories. *Conservation Biology*, **5,** 148–157.

Manabe, S. & Stouffer, R.J. (1996) Low frequency variability of surface air temperature in a 1000 year integration of a coupled atmosphere–ocean–land surface model. *Journal of Climate*, **9,** 376–393.

Manabe, S., Stouffer, R.J., Spelman, M.J. & Bryan, K. (1991) Transient response of a coupled ocean–atmosphere model to gradual changes of atmospheric CO_2. Part I: annual-mean response. *Journal of Climate*, **4,** 785–818.

Menaut, J.C., Lepage, M. & Abbadie, L. (1995) Savannas, woodlands and dry forests in Africa. *Seasonally dry tropical forests* (ed. by S.H. Bullock, H.A. Mooney and E. Medina), pp. 64–92. Cambridge University Press, Cambridge.

Middleton, N.J. & Thomas, D.S.G. (1997) *World atlas of desertification*. United Nations Environment Programme/Edward Arnold, London.

Mooney, H.A., Bullock, S.H. & Medina, E. (1995) Introduction. *Seasonally dry tropical forests* (ed. by S.H. Bullock, H.A. Mooney and E. Medina), pp. 1–8. Cambridge University Press, Cambridge.

Murphy, P.G. & Lugo, A.E. (1995) Dry forests of Central America and the Caribbean. *Seasonally dry tropical forests* (ed. by S.H. Bullock, H.A. Mooney and E. Medina), pp. 9–34. Cambridge University Press, Cambridge.

Myers, N., Mittermeier, R.A., Mittermeier, C.G., da Fonseca, G.A.B. & Kent, J. (2000) Biodiversity hotspots for conservation priorities. *Nature*, **403,** 853–858.

Olson, D.M. & Dinerstein, E. (1998) The global 200: a representation approach to conserving the Earth's most biologically valuable ecoregions. *Conservation Biology*, **12,** 502–515.

Olson, D.M., Dinerstein, E., Abell, R., Allnutt, T., Carpenter, C., McClenachan, L., D'Amico, J., Hurley, P, Kassem, K., Strand, H., Taye, M. & Thieme, M. (2000) *The global 200: a representation approach to conserving the Earth's distinctive ecoregions*. Conservation Science Program, World Wildlife Fund-US, Washington.

Olson, D.M., Dinerstein, E., Wikramanayake, E.D., Burgess, N.D., Powell, G.V.N., Underwood, E.C., D'Amico, J.A., Itoua, I., Strand, H.E., Morrison, J.C., Loucks, C.J., Allnutt, T.F., Ricketts, T.H., Kura, Y., Lamoreux, J.F., Wettengel, W.W., Hedao, P. & Kassem, K.R. (2001) Terrestrial ecoregions of the world: a new map of life on Earth. *BioScience*, **51,** 933–938.

Pennington, R.T., Prado, D.E. & Pendry, C.A. (2000) Neotropical seasonally dry forests and Quaternary vegetation changes. *Journal of Biogeography*, **27,** 261–273.

Pielou, E.C. (1979) *Biogeography*. John Wiley and Sons, New York.

Pressey, R., Ferrier, S., Hager, T., Woods, C., Tully, S. & Weinman, K. (1996) How well protected are the forests of north eastern New South Wales? Analyses of forest environments in relation to formal protection measures, land tenure and vulnerability to clearing. *Forest Ecology and Management*, **85,** 311–333.

Reynolds, J.R. & Mace, G.M. (1999) Risk assessments of threatened species. *Trends in Ecology and Evolution*, **14,** 215–217.

Ricketts, T.H., Dinerstein, E., Olson, D.M., Loucks, C.J., Eichbaum, W., DellaSala, D., Kavanagh, K., Hedao, P., Hurley, P.T., Carney, K.M., Abell, R. & Walters, S. (1999) *Terrestrial ecoregions of North America: a conservation assessment*. Island Press, Washington, DC.

Riitters, K., Wickham, J., O'Neill, R., Jones, B. & Smith, E. (2000) Global-scale patterns of forest fragmentation. *Conservation Ecology*, **4,** 3. http://www.consecol.org/vol4/iss2/art3 Accessed 29 August 2002.

Rundel, P.W. & Boonpragob, K. (1995) Dry forest ecosystems of Thailand. *Seasonally dry tropical forests* (ed. by S.H. Bullock, H.A. Mooney and E. Medina), pp. 93–123. Cambridge University Press, Cambridge.

Salafsky, N., Margoluis, R., Redford, K.H. & Robinson, J.G. (2002) Improving the practice of conservation: a conceptual framework and research agenda for conservation science. *Conservation Biology*, **16,** 1469–1479.

Sampaio, E.V.S.B. (1995) Overview of the Brazilian caatinga. *Seasonally dry tropical forests* (ed. by S.H. Bullock, H.A. Mooney and E. Medina), pp. 35–63. Cambridge University Press, Cambridge.

Sayer, J.A., Harcourt, C.S. & Collins, N.M. (1992) *The conservation atlas of tropical forests: Africa*. Macmillan, London.

Stouffer, R.J., Manabe, S. & Vinnikov, K.Ya. (1994) Model assessment of the role of natural variability in recent global warming. *Nature*, **367,** 634–636.

Udvardy, M.D.F. (1975) *A classification of the biogeographical provinces of the world*. IUCN Occasional Paper 18. International Union of Conservation of Nature and Natural Resources, Morges, Switzerland.

Wikramanayake, E., Dinerstein, E., Loucks, C.J., Olson, D.M., Morrison, J., Lamoreux, J., McKnight, M. & Hedao, P. (2002) *Terrestrial ecoregions of the Indo-Pacific. A conservation assessment. Conservation Science Program, WWF-US, Washington, DC, USA*. Island Press, London.

Wilson, K., Pressey, B., Newton, A., Burgman, M., Possingham, H. & Weston, C. (2005) Measuring and incorporating vulnerability into conservation planning. *Environmental Management*, **35,** 527–543.

BIOSKETCHES

Dr Lera Miles is a Senior Programme Officer in the Assessment and Policy Programme of UNEP-WCMC. She works on topics ranging from forest fragmentation to great ape conservation.

Dr Adrian Newton is a senior lecturer in conservation science at Bournemouth University, with research interests in the conservation ecology of tree species and forest ecosystems.

Dr Ruth DeFries is an associate professor at the University of Maryland, College Park, with joint appointments in the Department of Geography and the Earth System Science Interdisciplinary Center. Her research investigates the relationships between human activities, the land surface, and the biophysical and biogeochemical processes that regulate the Earth's habitability. She is interested in observing land cover and land use change at regional and global scales with remotely sensed data and exploring the implications for ecological services such as climate regulation, the carbon cycle and biodiversity.

Dr Valerie Kapos has worked in tropical forest ecology and conservation for more than 20 years. Her scientific publications include work on the impacts of forest fragmentation in Amazonia, on patterns of forest biodiversity and on conservation costs. She has also worked extensively on biodiversity indicators and on assessment of forest conservation status at global and regional scales and has contributed to a wide range of publications, including *World atlas of biodiversity* and *State of the world's parks*.

Corinna Ravilious and **Simon Blyth** work in the UNEP-WCMC GIS unit, principally on maintenance and analysis of global conservation data sets. **Ian May** is a GIS developer at UNEP-WCMC. He produced the fragmentation analysis for this paper, and is interested in developing new and innovative ways of making GIS data accessible to all users.

Dr Jamie Gordon is a researcher whose interests include dry forest tree diversity, the role of NGOs in forest conservation and the management of tropical forests in Mesoamerica and the Caribbean.

Editors: Peter Furley, John Grace and Patrick Meir.

This paper is part of the Special Issue, *Tropical savannas and seasonally dry forests: vegetation and environment*, which owes its origins to a meeting held at the Royal Botanic Garden, Edinburgh, in September 2003.