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Forest Conversion and Degradation in Papua New Guinea 1972–2002

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ABSTRACT

Quantifying forest change in the tropics is important because of the role these forests play in the conservation of biodiversity and the global carbon cycle. One of the world's largest remaining areas of tropical forest is located in Papua New Guinea. Here we show that change in its extent and condition has occurred to a greater extent than previously recorded. We assessed deforestation and forest degradation in Papua New Guinea by comparing a land-cover map from 1972 with a land-cover map created from nationwide high-resolution satellite imagery recorded since 2002. In 2002 there were 28,251,967 ha of tropical rain forest. Between 1972 and 2002, a net 15 percent of Papua New Guinea's tropical forests were cleared and 8.8 percent were degraded through logging. The drivers of forest change have been concentrated within the accessible forest estate where a net 36 percent were degraded or deforested through both forestry and nonforestry processes. Since 1972, 13 percent of upper montane forests have also been lost. We estimate that over the period 1990–2002, overall rates of change generally increased and varied between 0.8 and 1.8 percent/yr, while rates in commercially accessible forest have been far higher—having varied between 1.1 and 3.4 percent/yr. These rates are far higher than those reported by the FAO over the same period. We conclude that rapid and substantial forest change has occurred in Papua New Guinea, with the major drivers being logging in the lowland forests and subsistence agriculture throughout the country with comparatively minor contributions from forest fires, plantation establishment, and mining.

Abstract in Pidgin is available at http://www.blackwell-synergy.com/loi/btp.

Key words: land-use change; logging impact; Papua New Guinea deforestation rates; remote sensing; tropical forest; tropical forest mapping.

TROPICAL FORESTS ARE UNDERGOING WIDE-SCALE DEFORESTATION AND DEGRADATION, documented by the use of remote sensing data (Asner *et al*. 2005, Defries *et al*. 2007). Papua New Guinea (PNG) contains approximately half of the third largest extant area of tropical rain forest in the world, and is one of the most biodiverse and ecologically distinct forested regions (Brooks *et al.* 2006), highly important for both biodiversity conservation and carbon capture. Subsistence agriculture, forestry, fire, plantation development, and mining have all driven deforestation in PNG (McAlpine & Freyne 2001, Haberle 2007). Forest degradation has also occurred, largely as the result of conversion of primary forest into secondary forest by commercial logging. An intact canopy may regenerate within a few years after logging (Steininger 1996, Nepstad *et al.* 1999). However, beneath the canopy, logging results in reduced biomass, damage to other vegetation and soils, and increased vulnerability to both fire and subsequent conversion to grassland, scrub, or agricultural land that may persist for decades (Holdsworth & Uhl 1997, Nepstad *et al*. 1999, Asner *et al*. 2005, Defries *et al*. 2007). This damage requires logged forest to be treated separately from unlogged forest both from an ecological and carbon perspective (Foley *et al*. 2007).

The State of PNG is comprised of the eastern half of the island of New Guinea (termed here 'the Mainland region'), the islands of New Ireland, New Britain, and Bougainville, and many smaller islands (the 'Islands region'). The mainland of PNG possesses a rugged central mountain range reaching to more than 4500 m elevation that is flanked to the north and south by a comparatively flat lowland region. In contrast to other tropical regions, the majority of PNG's population still practice subsistence agriculture. Customary ownership of land is protected under the nation's Constitution (National Statistical Office 2000). The primary land-uses in PNG are subsistence agriculture and commercial forestry, although mining and commercial agriculture are also significant (McAlpine & Freyne 2001). In contrast to many other tropical regions, these land-use practices are still largely spatially segregated—the customary land-tenure system has to date largely prevented migration, settlement and subsequent clearance of logged forests (International Tropical Timber Organisation 2007). Due to the rugged and mountainous terrain, large areas of forest are relatively inaccessible to commercial forestry, hence PNG's timber resources are mostly confined to the coastal lowlands and offshore islands.

In the last decade the population of PNG has increased dramatically, as have timber exports from commercial forestry operations and oil palm exports from agricultural plantations (Gresham 1982, Filer 1997, Hunt 2002, FAO 2007; PNG Oil Palm Research Association, pers. comm.). Additionally there have been large forest fires, especially during the 1997–1998 El Niño event (Haberle *et al.* 2001). Prior to our study there had been no recent nationwide high-resolution assessment of PNG's forest extent and condition, the rate at which these forests are being cleared, or the impact of three decades of commercial export-driven logging. Despite this lack of

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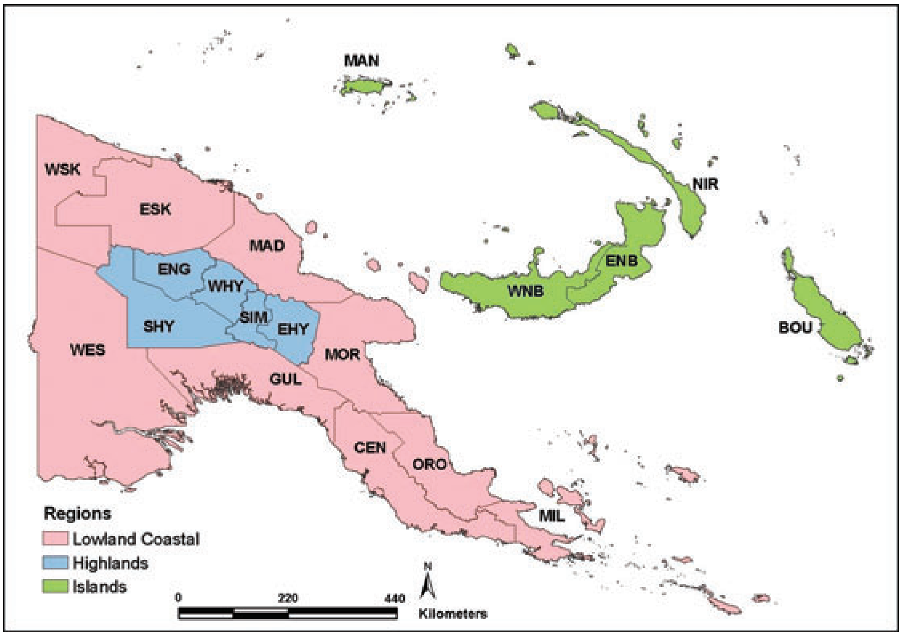

FIGURE 1. Provincial boundaries in PNG. Each province is shown colored by the broad region in which it is situated, the Islands, the Highlands, or the Lowland coastal regions. Provincial abbreviations: BOU = Bougainville; CEN = Central; EHY = Eastern Highlands; ENB = East New Britain; ENG = Enga; ESK = East Sepik; GUL = Gulf; MAD = Madang; MAN = Manus; MIL = Milne Bay; MOR = Morobe; NIR = New Ireland; ORO = Oro; SHY = Southern Highlands; SIM = Chimbu; WES = Western; WHY = Western Highlands; WNB = West New Britain; WSK = West Sepik.

data, the Food and Agriculture Organization (FAO) reported a low deforestation rate for 2000–2005 of 0.5 percent/yr (FAO 2005a). This low rate was suggested to be the result of an increased intensity of subsistence farming in response to population growth (McAlpine & Freyne 2001).

Our study maps recent (2002) forest extent and condition, and examines long-term forest change in PNG's forests overall, as well as in the extent of commercially accessible forest. We were able to conduct such a long-term high-resolution forest change analysis due to the availability of an Australian Army vegetation classification of very high-resolution aerial photography from the 1970s covering all of PNG (Coulthard-Clark 2000). Our primary objective in the study was to create and validate high-resolution land-cover maps to serve as baselines from which future change could be measured. Our second objective was to examine the extent and causes of deforestation and degradation across PNG's three distinct provincial regions: the islands, the highlands, and mainland lowlands (Fig. 1). For each discrete area of deforestation or degradation, we identified the main driver of forest change—either forestry, subsistence agriculture, plantation development, forest fires or mining activities, in PNG's overall forest extent, as well as in its commercially accessible forest extent. Our third objective was to estimate recent rates of deforestation and degradation in both commercially accessible and overall forest extent through the use of a driver-specific model, and to examine the relationship between population and subsistence-related clearance.

METHODS

PNG is located in the South Pacific, north of Australia and east of Indonesia. Annual mean rainfall varies from 1000 mm to > 8000 mm, and mean annual temperatures range from < 8°C to > 27°C in the lowlands, varying largely with elevation (McAlpine *et al.* 1983). The rugged and mountainous terrain prevailing over much of PNG means that regular acquisition of wall-to-wall cloud-free imagery is not possible, and automated classification of imagery is problematic (Colby & Keating 1998). Thus, although classification of sequential high-resolution satellite images can provide an accurate assessment of deforestation and degradation (Asner *et al.* 2005, Defries *et al.* 2007), the nature of the PNG landscape requires the adoption of novel techniques to map forest area and detect forest change.

A 'forest' is here defined as natural woody vegetation that has a contiguous tree canopy and a canopy height > 5 m. These forests are also known as tropical rain forest and are distinguished from open-sclerophyll forest, woodland, savannah, mangrove, and swamp vegetation. We confined our change analysis to rain forest.

CREATION OF 1972 LAND-COVER MAP.—The 1972 land-cover map was digitized from color separations of Australian Army (T601) 1:100,000 scale vegetation maps. These maps were created by the Australian Army using visual classification and manual delineation of polygon class boundaries of vegetation types discernible in very high-resolution (1–2 m) stereo aerial photography taken largely between 1972 and 1975, but predominantly (68%) in 1972–1973 (Coulthard-Clark 2000). The 23 percent of aerial photographs that were recorded prior to 1970 were predominantly located in remote and sparsely populated parts of Western province where little forest change has occurred. We have termed the resultant land-cover map a '1972' coverage. The vegetation classes used in this exercise were intact forest, mangroves, scrub, grassland, and water. For the change analysis, land-cover classes were combined into two categories: forest (rain forest) and nonforest (non-rain forest). All forests in the 1972 map were assumed to be primary forests as levels of commercial logging were comparatively low prior to this time (Hammermaster & Saunders 1995, McAlpine & Freyne 2001).

CREATION OF 2002 LAND-COVER MAP.—To create a new land-cover map of PNG, we acquired multiband imagery from the Landsat Enhanced Thematic Mapper Plus (ETM+) and Systeme Pour l'Observation de la Terre (SPOT) 4 and SPOT 5 sensors. Due to almost perpetual cloud-cover, we were unable to obtain suitable cloud-free 30-m resolution (15 m panchromatic) Landsat ETM+ imagery for the whole of PNG. In areas not covered by Landsat, we acquired SPOT 4 or SPOT 5 (20- and 10-m resolution, respectively) instead. About 18 percent of PNG was classified from imagery recorded in 2000–2001, 62 percent in 2002, and 20 percent in 2003–2007: accordingly we term the land-cover map '2002.' The location and date of capture of each image used is shown in Figure S1 and Table S1. Images recorded prior to 2002 were in general located in remote areas unlikely to have undergone substantial change. Images collected after 2002 were located across various parts of the country, some parts where forest change would be expected and some where no change would be expected.

In total we used 61 Landsat ETM+, 59 SPOT 4 and 5 images, and seven Landsat TM images to obtain cloud-free coverage for the whole of PNG. Each satellite image was orthorectified using 10–15 ground control points derived from the 1972 land-cover maps (Coulthard-Clark 2000) and a 90-m Digital Elevation Model (DEM) obtained from the Shuttle Radar Topography Mission (SRTM, Farr *et al.* 2007). The average root mean square error for the orthorectified imagery was 25–30 m for the Landsat and 15–20 m for the SPOT 4 and 5 imagery.

We applied a Tasseled Cap and Brovey transformation (Kauth & Thomas 1976) to our 2002 Landsat ETM+ imagery, and red/green/blue/infrared color enhancement to our SPOT 4 and 5 imagery. We used the object recognition software 'eCognition' (Definiens 2005) to automatically segment the satellite imagery into spatially continuous and spectrally homogeneous regions consistent with land-cover features, and to vectorize them into individual polygons. The process of image segmentation and vectorization is summarized in Figure 2.

Each polygon was classified using expert visual interpretation (Lu *et al.* 2004). Decision rules used to define land-cover classes are outlined in Table S2. Basic land-cover classes followed the classification system of Paijmans (1976), and were: tropical rain forest (referred to here as 'forest'), swamp forest, dry evergreen forest, mangroves, scrub, herbaceous swamp, nonvegetation, water, and grassland/savannah. Within the change analysis, land-cover classes were grouped into two categories: forest (rain forest) and nonforest (non-rain forest—dry evergreen forest, swamp forest, mangroves, scrub, herbaceous swamp, nonvegetation, water and grassland). An illustrated example of the classification process is contained in Figure S2.

CHANGE DETECTION.—The 1972 land-cover map was superimposed onto the 2002 map using a geographic information system, and areas of forest loss and gain that have occurred since 1972 were identified and automatically vectorized. The change detection process is depicted in Figure S3. Our resulting estimates of forest change are net forest losses because gain was subtracted from forest loss. Gross area converted (loss) and area reforested (gain) for each province are contained in Table S3.

ASSESSMENT OF DRIVERS OF FOREST CHANGE.—We mapped recent logging-related deforestation and degradation using the visual interpretation of logging roads, snig tracks, and canopy gaps to delineate a timber extraction radius (the area beyond a timber road or snig track in which timber has been extracted) for all commercial logging activity. Snig tracks, also known as skid trails, are temporary trails created by dragging felled trees or logs to a logging road. Forest within our timber extraction radius was designated as 'degraded' and clearances were designated as 'deforested' due to logging. In these areas the timber extraction radius was at maximum 500 m, but most often 100–300 m. Areas within logging concessions outside of this radius were assumed not to have been logged.

Older logging can be difficult to detect from Landsat imagery due to the closure of canopy gaps (Asner *et al.* 2002). We used logging roads identified during image classification (McGurk & Fong 1995, Stone & Lefebvre 1998, Souza & Barreto 2000, Laporte *et al.* 2007), PNG Forest Authority records of logging plans (National Forest Service 2000), and where visible, snig tracks, to delineate areas of older logging (> 5 yr). In these areas we manually delineated a timber extraction radius to a maximum of 500 m around logging roads.

In those areas where logging ceased more than a decade ago and where logging roads were themselves not visible, data from previous helicopter surveys of logging activity (Hammermaster & Saunders 1995) were used to demarcate logged areas. This use of the helicopter survey data only occurred in relatively few locations as in the majority of locations older roads are still visible because of recent use unrelated to logging, or because those areas that were logged in the 1980s have since been cleared.

Forest clearance as a consequence of subsistence agriculture frequently involves burning that commonly spreads a distance into adjacent vegetation. This clearance was designated as being subsistence-related. There were, however, some extensive fires in primary forest not associated with subsistence agriculture. In many locations, large areas of burned forest could be recognized by their distinct spectral response (Nepstad *et al.* 1999) coupled with reports from field workers. The identification of 'burned' forests was assisted in numerous locations by the presence of fire 'thermal hotspots' derived from the Moderate Resolution Imaging Spectroradiometer product (MODIS 14) that showed the location of recent fires

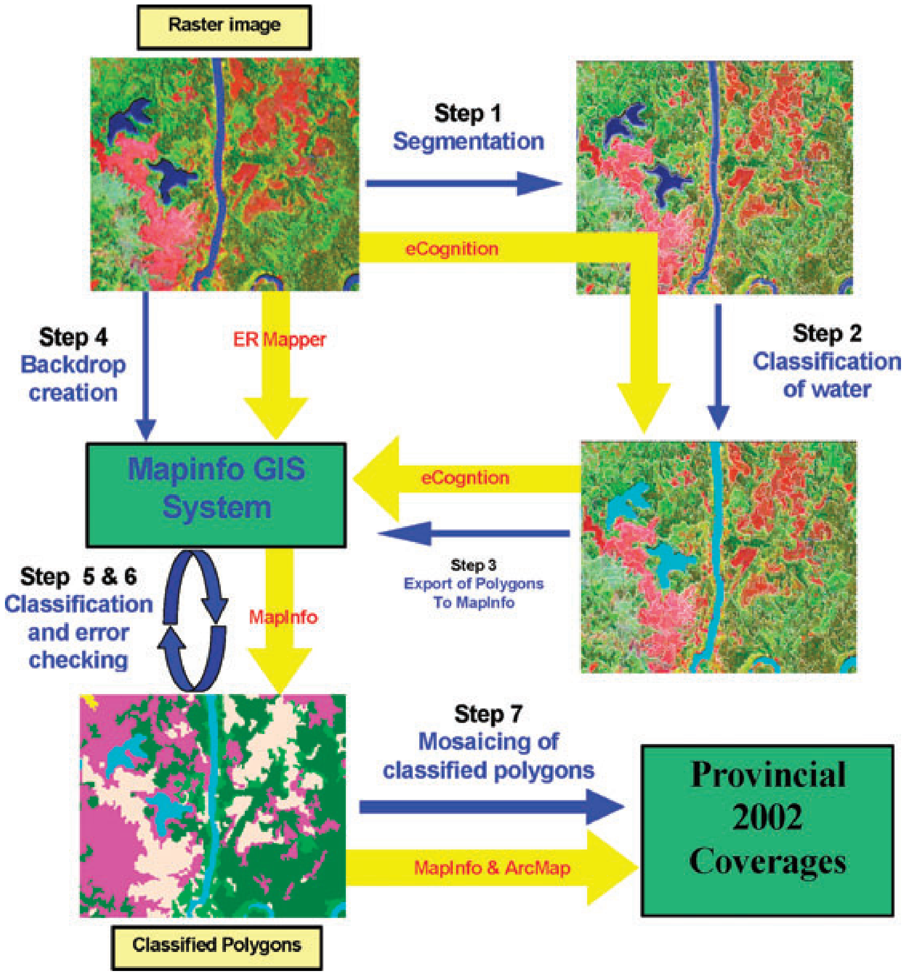

FIGURE 2. The process of image classification showing the seven principle steps.

(Giglio *et al.* 2003). In other locations, areas of fire-related loss were recognized due to their large distance (> 10 km) from zones of subsistence or commercial use, their distinct pattern, or in the case of montane forest loss, their location on the tops of mountain ranges, usually adjacent to existing grassland. We defined the upper montane zone in our land-cover maps as the region > 2800 m elevation, consistent with the definition of the 'Tropical Montane' life zone in PNG (McAlpine *et al.* 1983). The region > 2800 m elevation was delineated using a 90-m SRTM DEM (Farr *et al.* 2007).

Areas of deforestation that occurred within currently established plantations were deemed to have been cleared to create the plantation. Areas of forest replaced by the open pits of mining operations and associated infrastructure, as well as the tailings-related dieback downstream from the Ok Tedi mine were deemed to have been cleared due to mining. This assessment of mining-related deforestation does not include increased agriculture that may be associated with the mining projects (Dambacher *et al.* 2007).

Subsistence agriculture was usually discernible in the imagery. Areas of forest loss adjacent to either subsistence gardens or rural villages were deemed to be subsistence-related. Areas of deforestation that could not be attributed to other drivers of forest change were also assumed to have occurred through subsistence activities.

ASSESSMENT OF COMMERCIALLY ACCESSIBLE FORESTS.—Areas of polygonal karst, slopes too steep for mechanized logging, and Wildlife Management Areas were delineated as physically 'inaccessible.' Forests growing on polygonal karst in our 1972 and 2002 land-cover map were identified using a landform map (Loffler 1977) and our 2002 satellite imagery. Slopes too steep to log were identified using a slope surface derived from a 90-m resolution DEM. We created the DEM from Shuttle Radar Topography Mission (SRTM) data (Farr *et al.* 2007), corrected for the effects of radar shadow in steep valleys using a DEM created from 1:100,000 and 1:250,000 contour maps of PNG (Coulthard-Clark 2000). The resulting DEM was calibrated against a high-resolution (15-m) LIDAR DEM acquired in 2007 over a 60 × 60 km area centered on the Port Moresby region. We found that *ca* 95 percent of the logged areas in our 2002 land-cover map occurred on slopes < 25°. We therefore used 25° as the limit for commercial logging access in PNG. This concurs with the assessment in the Wet Tropics of

North Queensland that forests on slopes greater than 28° had a zero probability of being logged (Vanclay 1994).

Forested areas too small to support a commercial logging operation (50,000 ha) (World Bank & GoPNG 2001) were delineated as economically 'inaccessible.' The World Bank determined that commercially viable forestry operations in PNG required an annual timber extraction volume of 70,000 m^3 over 35 yr (World Bank & GoPNG 2001). We conservatively applied a smaller area (50,000 ha) as the lower limit for commercial viability since many concessions are only exploited for 10–15 yr and many logging companies operate under marginal economic conditions (Overseas Development Institute 2006).

RATES OF DEFORESTATION AND DEGRADATION.—Change rates are commonly calculated by dividing the measured area of forest loss as a percentage of forest area evenly over each year in the time period of the study (Puyravaud 2003). This method assumes constant decline over the time period. As our analysis was long term, the assumption of constant decline was implausible. This is because timber exports, oil palm exports, and population, associated with forestry, plantation, and subsistence clearance, increased substantially in the latter half of our 30-yr time period (Fig. S4). We therefore calculated change rates by apportioning the measured net area of deforestation and degradation to each year over the time period by modeling annual fire, forestry, plantation, mining and subsistence-related clearance.

We apportioned the total area of forestry-related deforestation and degradation to each year according to the volume of timber exported from logging concessions in that year (Gresham 1982, Filer 1997, Hunt 2002). The total area of plantation-related deforestation was apportioned on an annual basis according to the volume of oil palm exported 4 years later (PNG Oil Palm Research Association, pers. comm.). We lagged oil palm exports by 4 years to account for the delay between forest clearance for planting and harvest. The total area cleared due to subsistence agriculture was apportioned to individual years using the annual population estimates between 1972 and 2002 (FAO 2007). We apportioned the fire-related clearance to individual years based on the occurrence, intensity, and duration of El Niño events between 1972 and 2002 (Yue 2001). Mining-related clearance was apportioned evenly to each of the 30 years due to lack of data on the periodicity of mine-related deforestation. This is unlikely to impact our estimates of overall rates of forest change as the area cleared for mining is relatively small. We then estimated the annual rate of deforestation and degradation in each year as the percentage of the forest area from the previous year, which had been cleared or degraded by the following year (full methods are available in Appendix S1).

VALIDATION OF THE 2002 LAND-COVER MAP.—Validation of our 2002 classification was conducted using two low elevation aerial photographic surveys (resolution: 0.1–1 m) of 431 locations in West New Britain and Madang provinces during 2004 and 2008. All land-cover types in the 2002 classification were present in these surveys. The flight paths of the surveys are shown in Figure S5. In total 431 vertical photos were captured, mostly at *ca* 1000 m above the ground, and their location was recorded using a global positioning system (GPS). The area covered by each image was approximately 1 km^2. Each image was manually assigned to one of the classes used in the classification process. Where a photograph contained more than one class, the image was subdivided into nine equal rectangular areas and the central rectangle was classified. The classification was then compared to the classification of the satellite imagery over the same location.

ACCURACY ASSESSMENT OF 1972 VEGETATION CLASSIFICATION AND CHANGE DETECTION.—Assessing the accuracy of change detection procedures is difficult (Lu *et al.* 2004). This is especially so in PNG where additional recent imagery is difficult to acquire, and where suitably accurate data sets from the 1970s, independent of our own 1972 map, do not exist. Consequently we assessed change detection accuracy using the area of forest gained between 1972 and 2002. The 1972 land-cover map provided a reliable indication of actual vegetation cover across the entire nation due to its very high resolution and the extensive georeferencing and field verification undertaken during its production by the Australian Defence Force (Coulthard-Clark 2000). The change assessment, comparing our 1972 and 2002 land-cover maps, was bidirectional, estimating both loss and gain in forest cover. Forest gain occurred either through the conversion of nonforest to forest cover, or through error. Grassland could not become intact forest within a period of < 30 yr (Walker 1966, Gillison 1969, Duncan & Duncan 2000, Haberle 2007), so forest gain between 1972 and 2002 consisted of the regeneration of scrub to forest or was an artifact of error in the comparison. Forest gain therefore provided an upper limit on error in the change assessment.

RESULTS

OVERALL FOREST EXTENT IN 2002 AND THE ASSESSMENT OF DATA ACCURACY.—In 2002 there were 28,251,967 ha of rain forest in PNG (Fig. 3) with an additional 3,409,018 ha of swamp forest, 574,876 ha of mangroves, and 750,309 ha of dry evergreen forest. Of the rain forest, 25,332,253 ha were primary forest and 2,919,714 ha were secondary forest, degraded through logging (Table 1).

Our validation of the 2002 land-cover map found that 420 of the 431 images surveyed, or 97.7 percent, were correctly classified. Mismatches were found in 2.2 percent of the imagery classifications in which scrub had been confused with grassland. None of the forest classification samples were found to be erroneous.

The accuracy assessment of 1972 vegetation classification and change detection found that across the entire country 5.2 percent of total forest change was due to gain. We therefore estimated that the accuracy of change assessment was > 94.8 percent. An assessment of the source of all gain polygons indicated that 23 percent represented actual re-establishment of forest cover from shrub cover and the accuracy of change assessment was therefore greater than 96.0 percent. The positional accuracy of our imagery meant that forest boundary changes between the 1972 and 2002

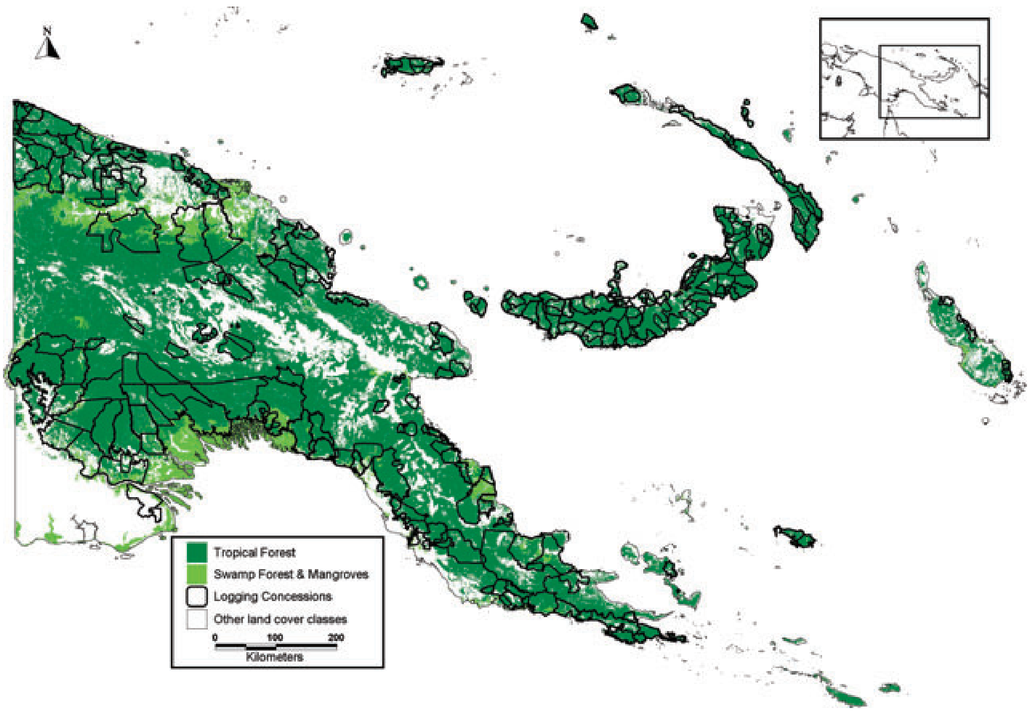

FIGURE 3. Distribution of tropical forest cover (primary and secondary) and designated logging concessions (allocated and unallocated) in Papua New Guinea.

land-cover maps of 60–100 m could be detected. Within these spatial limitations, we conclude the change detection accuracy was 96.0 percent.

CHANGES AND THEIR CAUSES IN OVERALL FOREST EXTENT BETWEEN 1972 AND 2002.—Between 1972 and 2002, a net 15.0 percent of primary rain forest was cleared and 8.8 percent degraded to secondary forest through logging (Table 1). Overall, 48.2 percent of this forest change was due to logging, 45.6 percent was related to subsistence agriculture, 4.4 percent due to forest fires, 1.2 percent due to plantations, and 0.6 percent due to mining. The percentage of net forest cleared and degraded due to forestry, plantation, subsistence agriculture, mining, and fire in each region and province is presented in Table 2. Between 1972 and 2002, 12 percent of primary forest was cleared for nonforestry purposes. The majority of this deforestation (88%) was due to subsistence gardening (Table 2). Between 1972 and 2002, 13 percent of primary upper montane forests were deforested mostly through burning. An example of this loss is shown in Figure S6.

Overall, logging resulted in the deforestation of 886,659 ha and the degradation of 2,919,714 ha of primary rain forest during the period 1972–2002 (Table 2). Approximately 23 percent of the total logged area was deforested within this period, either through logging, or through logging-related processes. The Island provinces, excluding Bougainville, where the oldest forestry concessions are located (National Forest Service 2000), had the highest percentage of deforestation or degradation due to logging between 1972 and 2002 (21–47%) (Table 2). Of this total change, 5.0 percent

TABLE 1. *The area of primary rain forest and primary rain forest accessible to commercial logging in PNG in 1972 and 2002, and change (%) due to both deforestation and degradation over this period. Swamp, mangrove, and dry evergreen forest are excluded. DF refers to the percentage of 1972 forest area deforested by 2002, DG refers to the area degraded, Tot. refers to the area deforested and degraded.*

	All rain forest					Accessible rain forest				
	1972 (ha)	2002 (ha)	Change (%)			1972 (ha)	2002 (ha)	Change (%)		
Region	Primary	Primary	DF	DG	Tot.	Primary	Primary	DF	DG	Tot.
Islands	4,885,727	2,699,103	21	24	45	2,877,354	1,064,717	22	41	63
Highlands	4,776,533	4,104,916	14	0	14	507,092	436,716	11	3	14
Mainland Lowland	23,565,330	18,528,234	14	7	21	10,090,542	7,182,347	12	17	29
Total	33,227,590	25,332,253	15	9	24	13,474,988	8,683,780	14	22	36

TABLE 2. *Forest change in PNG. Summary statistics 1972–2002. Change percentages are net percentages of primary forest area in 1972 that were deforested (DF), degraded (DG), deforested or degraded (Tot) by 2002 listed according to causes: F = Forestry, NF = nonforestry (Sub = Subsistence, Plant = Plantation, Min = Mining,), Tot = Total(F + NF). Zones: H = Highlands, LC = Mainland lowland coastal, I = Islands. *Percentage of forest in 2002, which is degraded. In Bougainville there has been no commercial logging since 1988 due to civil conflict and records of the extent of logging prior to the conflict are unreliable. For this reason all forest clearance in Bougainville is recorded as nonforestry related (34.04%) despite the likelihood that a percentage of this was forestry-related.*

						1972–2002 Change								
						DF								
		1972 Primary forest	2002 Forest Area			NF (%)								DF & DG
Province	Zone	area (ha)	Total (ha)	Primary (ha)	Degraded (ha) (%)*	Sub	Fire	Plant	Min	Tot	F (%)	Tot.(%)	DG F(%)	Tot. (%)
Southern highlands	H	2,126,200	1,877,043	1,869,724	7,319 (0.39%)	10.62	0.89	0	0	11.51	0.21	11.72	0.34	12.06
Enga	H	929,318	807,871	807,871	0	12.91	0.05	0	0.10	13.07	0	13.07	0	13.07
Western highlands	H	583,448	498,065	498,065	0	13.88	0.59	0	0	14.48	0.16	14.63	0	14.63
Chimbu	H	435,907	363,714	363,714	0	12.05	4.51	0	0	16.56	0	16.56	0	16.56
Eastern highlands	H	701,660	572,679	565,542	7,137 (1.25%)	17.29	0.68	0	0	17.97	0.41	18.38	1.02	19.40
Western	LC	5,194,206	4,575,048	4,022,038	553,010 (12.09%)	6.45	2.90	0	0.93	10.28	1.64	11.92	10.65	22.57
Gulf	LC	2,522,310	2,367,151	2,029,969	337,182 (14.24%)	5.03	0.02	0	0	5.05	1.10	6.15	13.37	19.52
Central	LC	2,382,124	1,963,004	1,783,019	179,985 (9.17%)	12.96	1.01	0.16	0	14.13	3.46	17.59	7.56	25.15
Milne Bay	LC	1,134,974	926,031	825,401	100,630 (10.87)	14.67	0.19	1.08	0.07	16.01	2.40	18.41	8.87	27.28
Oro	LC	1,793,923	1,559,545	1,469,458	90,087 (5.78%)	9.44	1.06	0.38	0	10.87	2.19	13.07	5.02	18.09
Morobe	LC	2,641,800	2,096,544	1,986,415	110,129 (5.25%)	15.77	1.84	0	0	17.61	3.03	20.64	4.17	24.81
Madang	LC	2,419,307	1,994,812	1,921,034	73,778 (3.70%)	15.13	0.49	0	0	15.61	1.93	17.55	3.05	20.60
East Sepik	LC	2,371,213	2,046,917	2,002,745	44,172 (2.16%)	12.73	0.36	0.12	0	13.21	0.47	13.68	1.86	15.54
West Sepik	LC	3,105,473	2,728,396	2,488,155	240,241 (8.81%)	10.17	0.58	0	0	10.75	1.39	12.14	7.74	19.88
Manus	I	150,700	124,000	102,381	21,619 (17.43)	11.22	0.00	0	0	11.22	6.49	17.72	14.35	32.06
New Ireland	I	820,606	646,802	387,405	259,397 (40.10%)	8.78	0.85	0.16	0.10	9.90	11.28	21.18	31.61	52.79
East New Britain	I	1,358,933	1,138,487	885,377	253,110 (22.23%)	7.45	0	0.58	0	8.03	8.19	16.22	18.63	34.85
West New Britain	I	1,847,904	1,499,119	857,201	641,918 (42.82%)	3.19	0.49	3.16	0	6.84	12.03	18.87	34.74	53.61
Bougainville	I	707,584	466,739	466,739	0	34.04	0.00	0.00	0	34.04	0	34.04	0	34.04
PNG Total		33,227,590	28,251,967	25,332,253	2,919,714 (10.33%)	10.83	1.04	0.28	0.15	12.30	2.67	14.97	8.79	23.76

was deforestation and 28 percent was degradation. Lowland coastal provinces on the mainland, where export logging expanded more recently (National Forest Service 2000), had 2–15 percent of primary forest deforested or degraded through logging (Table 2). Across the forests of the Lowland provinces, logging activity caused 0.4 percent deforestation and 7 percent degradation. In contrast, in the Highlands provinces, where logging has been primarily for local use, there was little forestry-related deforestation and degradation (0.03% and 0.3% respectively), with the notable exception of Mt Giluwe in Southern Highlands province where substantial forestry-related change has occurred.

After adjusting for regional effects, we found a curvilinear relationship between subsistence-related deforestation and provincial population density, with the highest density occurring in the Highlands provinces (Fig. 4). A least squares quadratic regression model with population density raised to 1.25 was highly significant ($R^2 = 0.98$, $F = 20.0$, $P = 3.69 \times 10^{-12}$, $N = 18$, $\alpha = 0.001$). Assumption of normality of the residuals was not rejected using the Shapiro–Wilk's test $w = 0.9783$ and $P = 0.9302$.

EXTENT, CHANGE AND ITS CAUSES IN COMMERCIALLY ACCESSIBLE FORESTS 1972–2002.—We estimated that in 1972, 13,474,988 ha (41%) of PNG's rain forest was potentially accessible to commercial logging. Between 1972 and 2002, a net 36 percent of accessible forest was degraded or deforested through both forestry and nonforestry processes (Table 1). The estimated accessible forest area in each province is shown in Table S4. The Islands provinces had the largest percentage (45–76%) of commercially accessible forests cleared or degraded and most of this change (68–92%) was due to forestry operations (Table S4).

RATES OF DEFORESTATION AND DEGRADATION.—Forest change rates (deforestation and degradation), for each year of our 30-yr time period based on our apportioning of total area cleared between 1972 and 2002 to individual years, are shown in Figure 5. Our forest change model suggests that the annual rate of forest change in total forest extent rose from 0.4 percent/yr in 1972–1973 to 1.4 percent/yr in 2001–2002, peaking in 1997–1998 at 1.8 percent/yr. Within commercially accessible forests, the estimated rate of

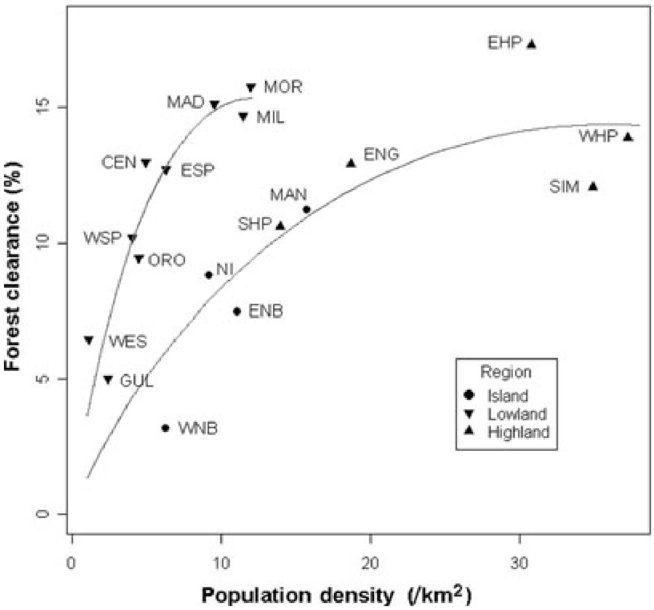

FIGURE 4. Percentage of primary rain forest cleared due to subsistence agriculture between 1972 and 2002 according to population density in each province in 2002. Bougainville is excluded from the plot as this island is ethnically and geographically part of the Solomon Islands, and civil war between 1988 and 1997 apparently caused a very high percentage of deforestation (34.0%) for population density (12.3 people/km^2) of the province. Each provincial data point is labeled according to its geographic region—Islands, Highlands, or Lowland coastal. Provincial abbreviations: CEN = Central; EHY = Eastern Highlands; ENB = East New Britain; ENG = Enga; ESK = East Sepik; GUL = Gulf; MAD = Madang; MAN = Manus; MIL = Milne Bay; MOR = Morobe; NIR = New Ireland; ORO = Oro; SHY = Southern Highlands; SIM = Chimbu; WES = Western; WHY = Western Highlands; WNB = West New Britain; WSK = West Sepik.

deforestation and degradation was consistently higher than in the total forest estate. Over the 1980s, we estimate that the annual rate of change within these forests rose from 0.7 percent/yr to 1.4 percent/yr. Dramatic increases in commercial logging over the 1990s drove the rate of change in commercially accessible forest to a 30-yr high of 3.4 percent/yr in 1997–1998, before lowering to 2.6 percent/yr in 2001–2002.

DISCUSSION

CREATION AND VALIDATION OF LAND-COVER MAPS.—As the validation of the 2002 land-cover map found no erroneous forest classifications, we conclude that our classification was robust because it was conducted at a scale where it is difficult for a trained human observer to be mistaken when discriminating between basic vegetation classes. Discrepancies arose only in the subjective location of fixed boundaries between transitional vegetation types. The largest limiting factor was the difficulty in obtaining cloud-free wall-to-wall imagery from a single year. Thus, it may only be possible to monitor tropical forest change across comparable regions using high-resolution imagery over a change period of at least 5 yr. Tucker and Townshend (2000) and Grainger (2008) argue that tropical forest change analyses require wall-to-wall and high-resolution image coverage if an accurate picture is to be gained. The substantial spatial heterogeneity we found in processes driving forest change, and the variation in the extent of forest change across the landscape, could not easily have been discerned using a sampling strategy, reinforcing their conclusion.

DRIVERS OF FOREST CHANGE.—The largest driver of forest change between 1972 and 2002 was logging. Our finding that logging accounted for a greater proportion of forest loss in the Islands provinces compared to the mainland coastal and Highlands provinces reflects the fact that the timber export industry has largely focused on lowland forests in coastal regions of the islands and mainland, rather than in the rugged and remote Highlands forests. This has largely been a consequence of accessibility. Our examination of change in accessible forests also found that timber resources in the Islands provinces are close to being fully exploited (Table 1). This decline encouraged the shift to logging in the mainland coastal provinces (Table S4). The high percentage of commercially accessible forests that has been deforested or degraded (36%) indicates that timber resources in PNG will be exhausted sooner than previous estimates of deforestation suggest (Wunder 2003, FAO 2005a). While a total of 8,683,780 ha of forest accessible to mechanized logging remain unlogged, 49 percent of this area has already been allocated to the commercial logging industry (Table S4; Fig. 3). The remainder occurs in relatively remote locations, is moderately inaccessible and/or in relatively small blocks. The substantial loss of PNG's accessible forests is important not only because it represents a loss of timber resource, but is also important for PNG's role as part of the Coalition of Rainforest Nations. The Government of PNG is a founding member of the Coalition of Rainforest Nations, a group of 15 nations exploring market-based mechanisms by which greenhouse gas emissions resulting from tropical deforestation and degradation can be stemmed (Laurance 2007). The area of extant forest where PNG can reasonably prevent deforestation and degradation is in the commercially accessible forests. This is because the inaccessible forests are either unlikely to be cleared or are subject to clearance as a result of subsistence agriculture or fire, two processes over which the central government has little control.

The large percentage of PNG's forests that have been degraded from their primary condition as a result of logging is also of concern because logged tropical forests are vulnerable to deforestation by burning (Holdsworth & Uhl 1997, Nepstad *et al.* 1999). Our study revealed areas of logged forest in New Ireland and New Britain provinces that had subsequently been burned. Fire risk is greatly increased by dry weather (Lewis 2006), and logging in seasonally dry regions is likely to be associated with burning of degraded forest. The largest area of unlogged accessible forests, 3,061,857 ha, occurs in Western Province (Table S4) and includes extensive seasonally dry forests (McAlpine *et al.* 1983). For this reason, these unlogged forests may be particularly vulnerable to conversion to savannah or

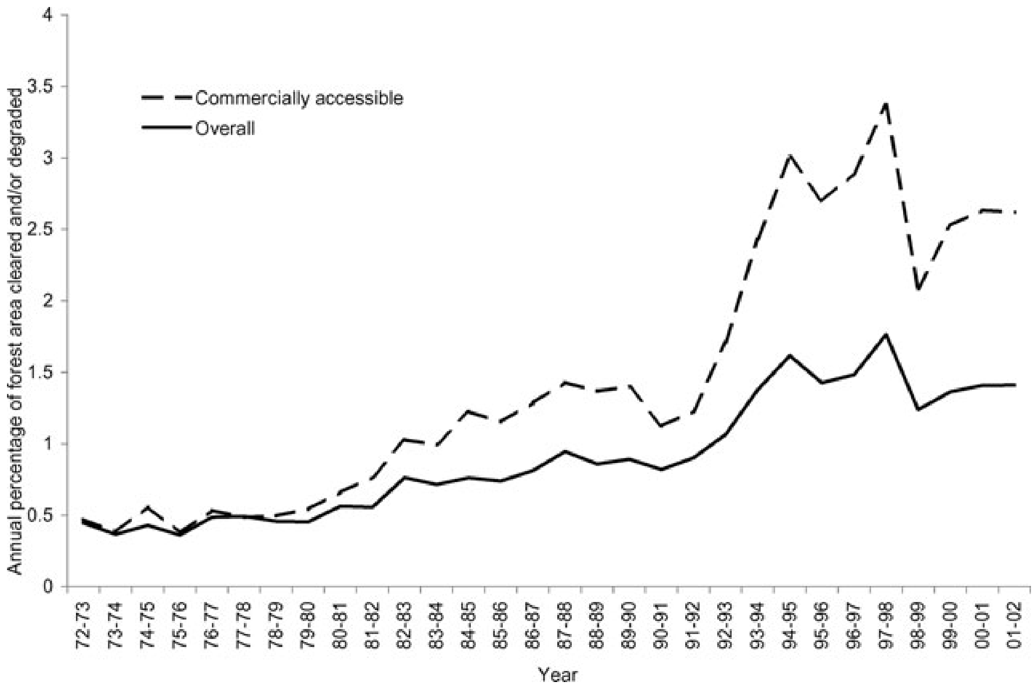

FIGURE 5. Annual forest change rates in commercially accessible as well as overall forest extent estimated from our forest change model. The annual change rates rise sharply in the 1990s due to the rapid expansion of logging in the commercially accessible forests and consequent increase in timber exports. A peak is reached in 1997–1998 due also to the severe El Niño event of the same period. The rapid decline after 1997–1998 marks the Asian financial crisis that resulted, until later in the study period, in substantially reduced timber exports.

grassland if wide-scale commercial logging and subsequent burning were to occur.

Our assessment of logged forest was limited in that we would have failed to detect older logging undertaken through the local use of portable sawmills not associated with logging roads or plans. However, this is a relatively minor component of the total national logging effort (Overseas Development Institute 2006). Our assessment of older logged forest also made use of PNG Forest Authority logging plans and hence depends to some extent on the accuracy of those logging plans. Timber exports from logging concessions have been independently monitored since 1993 (Overseas Development Institute 2006) and we found only relatively small areas of logging occurring outside designated areas. However, we may have failed to detect older unplanned logged forest where logging roads are no longer visible. Our assessment of the area of degraded forest may therefore be a small underestimate. Furthermore, although logging is still largely spatially segregated from other land-uses and customary ownership of land generally prevents migrants occupying logged forest, some secondary clearance for subsistence purposes no longer apparent in the imagery may have occurred in older logged forest. However, logging remains the primary driver in such a change.

The second largest driver of forest change was subsistence agriculture. Our finding that expansion of subsistence agriculture resulted in substantial deforestation contrasts with a previous land-cover change assessment in PNG, which concluded that the increase in PNG's population had been supported by agricultural intensification rather than expansion into previously uncultivated forest (McAlpine & Freyne 2001). This discrepancy is largely due to the necessarily coarser scale of mapping used in the previous study that was consequently unable to detect fine-scale clearances resulting from subsistence agriculture and logging (see discussion in Appendix S2).

Our finding of a significant curvilinear relationship between population density and subsistence-related clearance (Fig. 4) suggests that the exponential increase in population between 1972 and 2002 was supported by both additional forest clearance for gardening as well as agricultural intensification within nonforest areas at high population densities, especially in the Highlands provinces. This suggests that at a low regional population density, demand for food is met largely by an increase in the area under cultivation. However at high density this reaches a plateau and further population increases are supported through intensification, gardening in nonforest areas and uncultivated sites, or a trend toward cash crops. The population of PNG has been growing at an accelerating rate over recent decades (Fig. S4A) and shows little prospect of slowing in the next few years. For this reason the impact of subsistence-related clearance seems likely to be increasing beyond the estimates made in Table 1. Our finding is consistent with a previous forest change analysis conducted over Morobe Province (Ningal *et al.* 2007).

Large forest fires caused 4.4 percent of the change occurring in PNG's forests. Forest loss through burning was found to be the most important driver of change at high altitudes. High-altitude grasslands in PNG are relatively flammable and during droughts, fires ignited by humans or lightning have been recorded spreading into adjacent forests, causing the death of trees (Paijmans & Loffler 1972). We estimated that between 1972 and 2002, 13 percent of upper montane forest was lost. In many areas this was clearly associated with fire and it is likely that fires lit by people, especially during El Niño years such as 1997–1998, were the major cause of this change.

Clearing of forests for plantations was an important cause of change in some fertile lowland areas of West New Britain (3.2%) and Milne Bay (1.1%). The comparatively low level of deforestation due to agricultural plantations contrasts with neighboring tropical countries in the Southeast Asia region where clearance for oil palm has had a large impact on forest loss (Xiao *et al.* 2006). Our finding that commercial agriculture played only a relatively minor role contrasts with a previous forest change analysis of New Britain, which did not quantify change due to logging or subsistence agriculture (Buchanan *et al.* 2007), the two largest causes of forest change in both East and West New Britain (Table 2).

Mining has had intense local effects but the area directly affected has been small (0.2%), with most of this occurring in Western Province. Most infrastructure development has been in areas that were already cleared, and has therefore had little direct impact on forests.

Rates of forest change.—Our results suggest that the overall rate of forest change has been consistently higher over most of the study period than previously documented change rates including the 0.5 percent/yr reported consistently by the FAO (Wunder 2003, FAO 2005a). Our findings differ from the FAO change rate partly because the FAO estimates are based on linear extrapolation of the previous assessment of forest change between 1975 and 1996 (McAlpine & Freyne 2001), and include no additional information about forest change occurring after 1996 (FAO 2005b; see Appendix S2 for full discussion). Our model predicts the larger proportion of clearance occurring in recent years (Fig. 5). Our results are consistent with the New Britain deforestation rate (1990–2000) of 1.1 percent/yr estimated by Buchanan *et al.* (2007). Ideally, deforestation and degradation rates should be calculated by comparing two forest maps captured over a short time period (Puyravaud 2003). However, as our analysis was long term, we were limited to estimating change rates using a forest change model. Our change rates are conservative because we measured long-term net forest change that would have underestimated small-scale annual deforestation occurring after 1972 but which had regenerated a closed canopy by 2002.

Despite the finding that the deforestation rate in PNG was considerably higher than previously thought, our estimate of recent rates of deforestation is lower than that found elsewhere in Southeast Asia, with the deforestation rate in Borneo estimated at 1.7 percent/yr (Langner *et al.* 2007). This higher rate in Borneo may be because the commercial logging and oil palm industries have been established for a greater length of time than is the case in PNG. In addition, Borneo does not have customary ownership of land, which in PNG has generally prevented immigrants occupying land and subsequent secondary clearance of logged forest.

We found that the rate of forest change in commercially accessible forests was consistently higher than the overall rate of forest change (Fig. 5), indicating that timber resources are also being depleted at a far greater rate than previously thought. Since 2002, increases in population and logging activity are likely to have further increased these rates of change. As the inaccessible forests are either unlikely to be logged due to the combination of remoteness and ruggedness or are largely beyond the control of the central government due to customary land-tenure systems, logging in commercially accessible forests is the only area in which deforestation could be readily avoided. PNG needs therefore to urgently examine forestry management if it is to participate in market-based mechanisms to avoid deforestation and degradation.

Conclusion.—Our analysis does not support the theory that PNG's forests have escaped the rapid changes recorded in other tropical regions (FAO 2005a). As land is predominantly under customary ownership, ameliorating subsistence-related forest loss is a long-term challenge. Commercial logging, however, is within the control of the central government (Overseas Development Institute 2006). As a leader in the Coalition of Rainforest Nations (Laurance 2007) it is likely that addressing deforestation and degradation from commercial logging will be a priority for PNG.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article available at: www.blackwell-synergy.com/loi/btp

TABLE S1. *Date, type, location and area covered by satellite images used to produce the 2002 land-cover maps.*
TABLE S2. *Characteristics used to define land-cover classes.*
TABLE S3. *Gross forest area converted and reforested in each province.*
TABLE S4. *Area and change in commercially accessible forests 1972–2002.*
FIGURE S1. (A) Location and date of the Landsat and SPOT imagery used to produce the '2002' land-cover map; (B) Location of the Landsat and SPOT imagery used to produce the '2002' land-cover map.
FIGURE S2. An illustrated example of the classification process.
FIGURE S3. Change detection process.
FIGURE S4. (A) Population, (B) timber, and (C) oil palm exports in PNG between 1971 and 2002.

FIGURE S5. Flight paths for the low altitude aerial survey used in the validation of the classification.
FIGURE S6. An example of upper montane forest loss on Mt Kubor (3969 m), Western Highlands Province.
APPENDIX S1. Supplementary methods, including details of the change detection process, and the calculation of change rates.
APPENDIX S2. Discussion of the FAO change rate for PNG.

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