A bioregional analysis of the distribution of rainforest cover, deforestation and degradation in Papua New Guinea

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Abstract Papua New Guinea (PNG) is an extensively forested country. Recent research suggests that despite commencing a trajectory of deforestation and degradation later than many counties in the Asia–Pacific region, PNG is now undergoing comparable rates of forest change. Here we explore the bioregional distribution of changes in the forest estate over the period 1972–2002 and examine their implications for forest protection. This is undertaken through the development of a novel bioregional classification of the country based on biogeographic regions and climatic zones, and its application to existing forest cover and forest-cover change data. We found that degradation and deforestation varied considerably across the 11 defined biogeographic regions. We report that the majority of deforestation and degradation has occurred within all the lowland forests, and that it is these forests that have the greatest potential for further losses in the near term. The largest percentage of total change occurred in the east of PNG, in the islands and lowlands of the Bismarck, D’Entrecasteaux, East Papuan Islands and in the South-East Papua–Oro region. The only region with a significant highlands component to undergo deforestation at a comparable magnitude to the islands and lowland regions was the Huon Peninsula and Adelbert region. Significant changes have also occurred at higher elevations, especially at the interface of subalpine grasslands and upper montane forests. Lower montane forests have experienced proportionally less change, yet it is these forests that constitute the majority of forests enclosed within the protected area system. We find that protected areas are not convincingly protecting either representative areas of PNG’s ecosystems, nor the forests within their borders. We conclude by suggesting a more expansive and integrated approach to managing the national forest estate.

Key words: bioregional classification, conservation, deforestation, degradation, forest-cover change, Papua New Guinea, protected area.

INTRODUCTION

The forests of the island of New Guinea (Papua New Guinea (PNG) and West Papua together) constitute the third largest expanse of tropical rainforest on the planet after the Amazon and Congo forests (Brooks et al. 2006). Papua New Guinea comprises the eastern half of the island of New Guinea. Papua New Guinea’s forests are a vital natural resource for the human population that they sustain, the wide biological diversity they contain, the ecological services they provide and their global role in maintaining climatic stability (Hunt 2006). These forests provide food and building materials for a large proportion of PNG’s six million people. They also provide an important safety net when crops fail, in times of economic crisis or conflict, and when natural disasters strike. They provide a range of both local and global environmental benefits that are often overlooked and remain economically undervalued. These services include carbon sequestration, watershed protection, water filtration, coastal and reef protection, preservation of fish stocks, and soil stability and fertility. They also provide commercial timber – approximately 2.5 million cubic metres of raw logs were exported in 2008, with a FOB value of US$184 million (SGS 2008).

Rapid and substantial deforestation and logging-related degradation has occurred in PNG’s forests over the past 30 years (Shearman et al. 2009). Between 1972 and 2002, a net 15% of PNG’s tropical forests were cleared and 8.8% were degraded through logging. While Shearman et al. (2009) focused on the distribution of this change according to measures of accessibility and within three altitudinal classes (lowland, lower montane and upper montane), the
manner in which it has impacted on the different floristically, climatically and geologically distinct landscapes of PNG is yet to be examined and is the focus of this study.

Bioregional classification of PNG’s forest ecosystems

The forests of PNG are some of the most biologically diverse ecosystems in the world (Davis et al. 1995; Myers et al. 2000). The country has over 2000 species of orchids, the second highest of any country behind Ecuador and a comparable number of fern species (Papua New Guinea National Assessment Report 2006). These forests provide the habitat for the majority of PNG’s birds (733 species), mammals (304 species) and herpetofauna (612 species) (Sekhran & Miller 1994; Allison 2007; Bishop Museum 2009). The forests, and more broadly the flora of New Guinea, is more closely allied to the flora of East Asia than to that of the Australian continent. For this reason it has been termed ‘Malesian’, part Asian and part Melanesian. The predominantly Gondwanic montane flora of New Guinea is the most significant exception to this derivation (Linder & Crisp 1995).

Papua New Guinea possesses a range of forest communities that vary both structurally and floristically as well as in the fauna they support. These geographical and floristic differences allow the landscape to be viewed as a series of ‘bioregions’. Bioregionalization aims to reduce the Earth’s ecosystems into a number of smaller subsystems that are internally relatively more homogeneous with respect to characteristics of interest (Mackey et al. 2008). Division into such subsystems allows the provision of national level information relevant to systematic planning for the conservation of biodiversity (Olson & Dinerstein 1998; Margules & Pressey 2000; Olson et al. 2001; Whittaker et al. 2005) and related natural ecological processes (Mackey et al. 2001; Land and Water Australia 2002). Biogeographical regions are also considered useful for identifying areas that can be subject to similar natural resource management prescriptions and for extrapolating the results of site-scale experiments (Hobbs & McIntyre 2005).

Various approaches have been developed for mapping the distribution of biological and ecological phenomena. According to Mackey et al. (2008), a land surface can be geographically delineated biotopically on the basis of discontinuities in abiotic environmental factors, such as climate or geology, bioconotically using discontinuities in the distribution of biota (Clifford & Stephenson 1975), or some combination or integration of the two. At larger cartographic scales, mapped units are referred to as regional ecosystems, land systems or landscape ecosystems. At smaller geographical scales, the stated aim of such exercises is usually to map geographic entities referred to as bioregions, biomes, or, more recently, ecoregions.

In PNG, the principle biotop factors influencing the distribution of biota are climate and geological history. It has long been observed that vegetation, in terms of its structure and floristics, changes continuously across the landscape in response to climatic gradients (Gleason 1939). Two of the most significant environmental gradients that drive these vegetation changes are temperature and rainfall and the interaction between them (Gleason 1939; Specht 1970, 1981; Woodward 1987; Box et al. 1993; Hoffman & Parsons 1997; Walther et al. 2002; Rehfeldt et al. 2006). The flora of PNG varies considerably with temperature, which is itself strongly correlated with elevation (McAlpine et al. 1983). Consequently, the broadest and most commonly used vegetation classification has been its division into lowland, lower montane, upper montane and alpine elevational zones (Paijmans 1976). Rainfall, particularly rainfall seasonality, also has a strong influence of the geographic distribution of plant and animal communities in PNG (Paijmans 1976; Johns 1982). For these reasons, both temperature and rainfall were incorporated into our division of forest cover into climatic domains.

The considerable complexity of PNG’s geological history is of paramount importance in the distribution of plant and animal communities. By the early 1970s the principle geological structures of PNG had been recognized (Oliver & Bain 1972). These boundaries were later used both as the basis for the assessment of soil types (Bleeker 1983) and regional geomorphology (Loffler 1977). These basic regions are presented in Figure S1. While the existence of these general regions is still accepted and forms the basis of the bioregional classification used in this study, the understanding of their tectonic history was revised by Pigram and Davies (1987), with major ecological implications. Prior to this work, the mountainous belt forming the spine of the island of New Guinea was regarded as the result of a simple continent–island arc collision. Pigram and Davies (1987) described the orogeny as consisting of a southern part (the Australian craton) and a northern part made up of at least 32 tectonostatigraphic terranes – fault-bounded geological provinces with histories independent from their surrounding geologic features. The New Guinea terranes, including intrusive and metamorphic rocks, formed and sometimes amalgamated with others some distance from their present position and subsequently accreted to the craton margin during different periods over the last 40 million years. Figure S2 presents a stylized map of the location of the different terranes across the island of New Guinea derived from Heads (2001a). Each terrane presumably possessed a different biota from the ‘mainland’ to which it docked,
resulting in the introduction and inclusion of new flora and fauna to the mainland, and providing new isolated habitats and opportunities for speciation. In addition, the uplifting and downwarping activity associated of docking would have had indirect impacts on climate that would have in turn, had impacts on speciation and biota distribution (Van Welzen 1997).

Over recent decades there has been a growing recognition that the current distribution of PNG’s biota often correlate with tectonic patterns associated with groups of terranes, with breaks in ranges often coinciding with the craton margins (Van Welzen 1997; Heads 2001a,b), although recent analyses of biogeographic distributions in other regions of the South West Pacific suggest that some species associations are far more complex than simple correlations with tectonic patterns (Murienne et al. 2005; Ladiges & Cantrill 2007). Nevertheless, in the absence of a more systematic biogeographic regionalization of the flora of PNG (Heads 2001a), tectonic and geological history of the island of New Guinea has been used to explain the observed patterns of biodiversity of birds (Heads 2001b), reptiles (Allison 1993; Heads 2001b), mammals (Flannery 1990; Heads 2002), freshwater fauna (Polhemus 1996; Polhemus & Allen 2004) and a variety of plants (Van Welzen 1997) including orchids and rhododendrons (Heads 2001b). The approach used in this study is a synthesis of these works, resulting in a geologically based regionalization that is used to distinguish between assemblages of various plant and animal groups.

The only previous assessment of forest types in PNG that possessed some biogeographical distinctions was the Forest Inventory Mapping System (FIMS) analysis (Hammermaster & Saunders 1995) that divided the country into 42 zones. These zones, displayed in Figure S3, are essentially subdivisions of cadastral provincial boundaries and were based on dominant species type. Hammermaster and Saunders (1995) recognized that these divisions were quite subjective. Given that FIMS was aimed at the commercial assessment of the forest estate, the zones were heavily influenced by the location of timber inventory data. The FIMS mapping of forest boundaries was coarse, often consisting of ‘forest complexes’ containing a mixture of forest and other land types. For this and a variety of related reasons, FIMS cannot be used for accurate change detection. A more recent spatially explicit forest-cover map of PNG created using wall-to-wall high-resolution imagery has since been created, in part, to overcome the limitations of the FIMS forest mapping (Shearman et al. 2009).

A more recent compilation of biogeographical information for PNG was synthesized by Olson et al. (2001) in the designation of the World Wildlife Fund ecoregions. Olson et al. (2001) defined an ecoregion as a ‘large unit of land or water containing a geographically distinct assemblage of species, natural communities, and environmental conditions’. The boundaries of an ecoregion are not fixed and sharp, but rather encompass an area within which important ecological and evolutionary processes most strongly interact. In the case of PNG, these ecoregions were separated on the basis of biological data, paleoenvironments and expert opinion. The ecoregion analysis of Olson et al. (2001) for PNG does not possess a sufficiently fine resolution of climatic variables to adequately describe variation in forest communities, and its boundary delineation is relatively coarse. In addition, recent work on the beta diversity of lowland forests both in PNG (Novotny et al. 2007) and the Western Amazon (Condit et al. 2002) suggested that it is often comparatively low and that therefore little variation can be expected in species composition across the large lowland forest expanses of the Sepik–Ramu basins and the Western/Gulf areas. There is therefore a need for a refined map of bioregions in PNG that incorporates better resolution climatic information, and a more comprehensive mapping of geologic and tectonic features of PNG.

Here we adopt a biotopic division of the country into biogeographic regions on the basis of its geological history of accretion, followed by a division of these biogeographic regions into ‘biomes’ on the basis of the climatic zones that they encompass. These climatic zones are based on temperature and rainfall domains. We then incorporate this bioregional classification with the results of a long-term forest mapping and forest change analysis (Shearman et al. 2009) to:

1. Produce a map of ecologically and biotically distinct forested zones;
2. Measure long-term deforestation and degradation in each identified forest zone and examine the implications of these data;
3. Assess the representativeness and success of PNG’s protected area system within each forest zone and across the forest estate in general.

METHODS

Summary

A new regionalization was defined through the juxtaposition of two surfaces; one identifying 11 biogeographical zones and the other identifying 11 climatic domains. The combination of both datasets allowed assessment of long-term forest change in 81 separate regions or ‘biomes’ of the country. Note that while there were 121 possible combinations of biogeographical zones and climatic domains, only 81 biomes actually exist – the difference due to the biogeographical zones not actually containing some of the climatic domains.

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We conducted a biogeographical classification of PNG by dividing the landscape into tectonically and geologically distinct regions through the synthesis of past tectonic and geological mapping studies. Our climatic classification was synthesized by dividing the landscape into distinct, biologically relevant, rainfall and temperature zones using Worldclim grided temperature and rainfall surfaces (Hijmans et al. 2005). We then combined our biogeographic and climatic classifications into a single map showing distinct biogeographic–climatic zones that we refer to as ‘biomes’. We then combined our biome map with the 2002 forest map and change analysis of PNG (Shearman et al. 2009) to produce a map of ecologically distinct forest biomes and to examine long-term change within these biomes. We also examined the representation of forest, forest-cover change and forest biomes in PNG’s protected area system. The 2002 forest map defines ‘forest’ as natural woody vegetation that has a contiguous tree canopy and a canopy height >5 m. These forests are also known as tropical rainforest and are distinguished from open sclerophyll forest, woodland, savanna, mangrove and swamp vegetation. The change analysis was confined to rainforest.

Our methodology is therefore divided into four sections: (i) biogeographic classification; (ii) climatic classification; (iii) forest biome area and change; and (iv) forest area and change in protected areas.

Biogeographical classification

Our biogeographical classification was conducted by synthesizing previous mapping of tectonic boundaries, primarily following the boundaries of terrane groups first described by Ollier and Bain (1972) and explained by Pigram and Davies (1987). Where possible, existing gaps in forest cover were used as the location of a zone boundary, such as the Markham Valley or the Watut-Tauri Gap, the boundary between the Central Ranges and the Owen Stanley terrane (Flannery 1990).

A 90-m resolution digital elevation model (DEM) derived from the shuttle radar topography mission data (Farr et al. 2007) was used to demarcate altitudinal zones. The separation of the lowland zones from highland zones, such as the Markham Valley or the Watut-Tauri Gap, the boundary between the Central Ranges and the Owen Stanley terrane was defined as occurring at 1000 m altitude: the boundary between ‘low altitude forest’ and ‘lower montane forest’ (Paijmans 1976; Hammermaster & Saunders 1995).

The D’Entrecasteaux Islands were separated from Normanby Island (and the rest of the Papua islands) on the basis of the distribution of freshwater fauna (Polhemus & Allen 2004) and amphibians (Allison 1993) that both suggested that these islands possess a fauna radically distinct from the neighbouring islands and the mainland, thus representing a distinct evolutionary history. The distinct ultramafic zone in Oro/Morobe was defined as a separate zone because of its distinct assemblage of plant and animal species. The boundaries of these 11 biogeographical zones are displayed in Figure 1 and each is described below. The boundaries can be obtained in geographic information system format (ESRI Shapefile) from the authors.

Biogeographical zone descriptions

1. Sepik–Ramu–Markham Basins. These large structural basins lie to the north of the Central Ranges and are predominantly drained by the Sepik, Ramu and Markham rivers. They also contain the Torricelli and Bewani coastal ranges. While it could be argued that these coastal ranges should be treated as a distinct region on the basis of their relatively recent accretion history and upland endemics, they contain a relatively small montane region. While it is tempting to create many more zones for the numerous small mountainous outliers that exist throughout the country, to do so would reduce the utility of a national classification.

2. Fly–Gulf. The Fly, Strickland, Purari and Kikori rivers drain this huge series of connected lowland basins. Created by the collision of the Central Highlands terrane with the Australia craton, this region...
supports the largest extent of contiguous lowland forests in the country.

3. Central Highlands. This area includes the Central Dividing Range between the upper Sepik and Fly rivers in the west and the Bulolo River in the east, containing the headwaters of the Kikori and Purari rivers at elevations above 1000 m. This is a complex uplift, with several well-separated areas of extremely high terrain centred around peaks, such as Mt Wilhelm (4509 m) and Mt Giluwe (4367 m), and contains an extensive exposure of uplifted Palaeozoic basement in the Kubor Anticline (Hill & Hall 2003).

4. Huon Peninsula and Adelbert Ranges. The Huon Peninsula contains the Finisterre and Saruwaged Mountains, and probably docked to the mainland at approximately the same time as the Adelbert Ranges in Madang Province. This northern coastal mountain block, running from east of the Sepik River delta to the tip of the Huon Peninsula, corresponds to the Adelbert–Finisterre Terrane of tectonic geologists and is considered to be an accreted sector of a formerly separate island that was sutured to New Guinea in the Late Miocene to Pliocene (Hill & Hall 2003).

5. Owen Stanley Ranges. The central mountain chain of the Papuan Peninsula, comprised of uplifted ophiolites and subduction melange, is an area of rich endemism in all groups.

6. South-East Papua Lowlands. Flannery (1990) observed that South-East New Guinea (south-east of a line: Kerema–Garaina) is biogeographically distinct from the central PNG highlands. This area extends from the Watut-Tauri Gap all the way to Milne Bay and Normanby Island in the east, including the lowlands of the Popondetta plains and the southern coast of Central Province. Flannery (1990) first used the term ‘Watut-Tauri Gap’ to describe the biogeographical boundary between the birds of the Papuan Peninsula and those of the central Highlands of PNG. This boundary correlates with the craton margin (Heads 2001b).

7. Bowutu Ultramafic Belt. Allison (1993) observed that the Bowutu Mountains/eastern Kuper Range (Bowutu terrane, consisting of the Papuan Ultramafic Belt) form a major centre of diversity for frogs and lizards, with 20 frogs and 10 lizards endemic. The presence of ultramafics on the Earth’s surface is of great tectonic significance as they are sections of oceanic crust and upper mantle that have been uplifted and obducted onto land (rather than subducted below it). This has occurred at plate margins during island arc collision, and accreted arc terranes and orogenic belts frequently include ophiolites. Vegetation communities found on ultramafic rock types often contain a considerable degree of endemism. Soils derived from these rocks contain large concentrations of some elements (e.g. iron, magnesium, nickel) and are deficient in others (e.g. calcium). For plants to survive on these substrates adaptations are needed to cope with toxic levels of some abundant elements and deficiencies in others. Botanists have long recognized that these northern New Guinea ultramafics were strong foci of endemism (e.g. Airy Shaw 1980; Prance & Campbell 1988), and it was considered that much of this endemism was the result of edaphic rather than historical factors. Polhemus (1996) pointed out that although many animals (e.g. Parotia lawesii helena) show similar distributions, this might reflect biogeographic rather than edaphic factors.

8. East Papua Islands. This vast maritime region contains the relatively less diverse, but faunally distinct islands of Misima, the Trobriands, Woodlark Island, the Louisiade Archipelago, east to Sudest and Rossel Islands.

9. D’Entrecasteaux Islands. This is a chain of high islands with predominantly metamorphic geology, and lies immediately north of the eastern Papuan Peninsula. Recent collections have demonstrated the presence of endemic mammals, fishes, Heteroptera and Zygoptera (Polhemus & Allen 2004), but have also shown that this endemism is confined to Goodenough and Ferguson islands, with Normanby Island forming instead part of the Cloudy Mountains area of endemism (South-East Papua Lowlands).

10. Southern Bismarck Island Arc. This area contains the island of New Britain as well as its surrounding islands. Despite its proximity, 70% of the bird species on the New Guinean mainland adjacent to New Britain are not represented there (Heads 2001b). Gressitt (1982) considered that the absence of many New Guinea animals from the Bismarck Archipelago is ‘puzzling’.

11. Northern Bismarck Island Arc. Extending from Manus in the west, through the New Ireland chain to Bougainville in the east, this series of terranes are broadly related to each other in possessing a relatively lower flora diversity and affiliations with the mainland.

A bioclimatic domain classification of PNG

Our bioclimatic classification was based on rainfall and temperature. Rainfall in PNG is generally high (McAlpine et al. 1983). A critical factor for plant growth, and therefore a feature of rainfall patterns that
have a bearing on vegetation distribution, is likely to be the amount of rainfall occurring in the driest period of the year. A grid of rainfall of the driest quarter in PNG was produced using the ANUCLIM programme and a 1-km resolution DEM (Houlder et al. 2000) and classified into four classes. These classes are displayed in Table 1.

Table 1. Rainfall classes used in defining bioclimatic zones

<table>
<thead>
<tr>
<th>Rainfall class</th>
<th>Precipitation of the driest quarter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>55–750</td>
</tr>
<tr>
<td>Moderately low</td>
<td>750–950</td>
</tr>
<tr>
<td>Moderately high</td>
<td>950–1200</td>
</tr>
<tr>
<td>High</td>
<td>1200–1771</td>
</tr>
</tbody>
</table>

Temperature in PNG is strongly correlated with altitude (McAlpine et al. 1983). Both Pajimans (1976) and Hammermaster and Saunders (1995) defined the boundary between ‘low altitude forest’ and ‘lower montane forest’ as occurring at 1000 m altitude, and between ‘lower montane forest’ and ‘montane forest’ as occurring at 3000 m altitude. In order to be consistent with both these classifications, the temperature surface used to produce the bioclimatic zones was derived from the 90-m resolution shuttle radar topography mission DEM (Farr et al. 2007) using the temperature–altitude correlation equations from McAlpine et al. (1983). The classification of mean annual temperature, derived from altitude, was initially divided into classes based on temperatures occurring at the 0, 1000 and 3000 m altitudes. However, 2800 m rather than 3000 m was chosen as the biological break between the montane and lower montane climatic zones to be consistent with the definition of Holdridge’s ‘Tropical Montane’ life zone in PNG (McAlpine et al. 1983).

The altitude classes and their corresponding ranges in mean daily minima and mean daily maxima estimates derived from McAlpine et al. (1983) are presented in Table 2.

Table 2. Temperature classes used in defining bioclimatic zones and their corresponding mean daily temperature range and corresponding altitude range

<table>
<thead>
<tr>
<th>Class</th>
<th>Altitude range (m)</th>
<th>Range in average mean daily temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper montane</td>
<td>2800–4500</td>
<td>1.3–11.6 (&lt;11.6)</td>
</tr>
<tr>
<td>Lower montane</td>
<td>1000–2800</td>
<td>11.6–22.5</td>
</tr>
<tr>
<td>Lowland</td>
<td>0–1000</td>
<td>22.5–28.5 (&gt;22.5)</td>
</tr>
</tbody>
</table>

Both the temperature and rainfall classes were combined to produce a bioclimatic zonation of PNG based on rainfall in the driest quarter and mean annual temperature (derived from altitude). This resulted in the delineation of 11 bioclimatic zones. The parameters used to define these classes are displayed in Table 3 and the resulting map in Figure 2. Zones 1–3 correspond to the Pajimans’ (1976) upper montane zone, zones 4–7 correspond to the lower montane zone, and zones 8–11 correspond to the lowland zone.

**Biome classification**

Using a geographic information system we intersected the digital map of biogeographic zones with our digital map of bioclimatic zones. The resulting map formed our final biome classification.

**Forest bioregion area and change**

Using a geographic information system, we clipped the digital map of bioregions with the 2002 forest area map to produce a map of forest bioregions. We then clipped a map of long-term forest-area change (deforestation and degradation) occurring between 1972 and 2002 with our bioregion map to measure net area deforested and degraded in each forest bioregion. There were a number of locations where a particular zone in a particular biogeographic region was represented by only a small forest area (<1000 ha) but was contiguous with a larger forest zone. In these locations we reclassified the very small area of forest and included it as part of the larger adjacent zone.

We also calculated the area of commercially accessible unlogged forest extant (both allocated and unallocated) in each of these bioregions to enable the assessment of the potential impact of systemic logging over PNG’s entire forest estate. Accessible forests were demarcated using the mapping described by Shearman et al. (2009), where forest growing on polygonal

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Table 3. The parameters used to define Bioclimatic zones for Papua New Guinea

<table>
<thead>
<tr>
<th>Bioclimatic zone</th>
<th>Temperature class</th>
<th>Rainfall class</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Upper montane</td>
<td>Moderately low</td>
</tr>
<tr>
<td>2</td>
<td>Upper montane</td>
<td>Moderately high</td>
</tr>
<tr>
<td>3</td>
<td>Upper montane</td>
<td>High</td>
</tr>
<tr>
<td>4</td>
<td>Lower montane</td>
<td>Low</td>
</tr>
<tr>
<td>5</td>
<td>Lower montane</td>
<td>Moderately low</td>
</tr>
<tr>
<td>6</td>
<td>Lower montane</td>
<td>Moderately high</td>
</tr>
<tr>
<td>7</td>
<td>Lower montane</td>
<td>High</td>
</tr>
<tr>
<td>8</td>
<td>Lowland</td>
<td>Low</td>
</tr>
<tr>
<td>9</td>
<td>Lowland</td>
<td>Moderately low</td>
</tr>
<tr>
<td>10</td>
<td>Lowland</td>
<td>Moderately high</td>
</tr>
<tr>
<td>11</td>
<td>Lowland</td>
<td>High</td>
</tr>
</tbody>
</table>
karst, slopes greater than 25° and forested areas smaller than 50 000 ha were deemed commercially inaccessible.

Using a geographic information system we clipped our 2002 forest bioregion and 1972–2002 forest change map with a digital map of protected area boundaries in PNG. The area of forest cover, degradation and net deforestation within each of the PNG protected areas was also calculated. The locations and names of these protected areas are displayed in Figure S4.

The term ‘forest change’ is used to refer to the total area of rainforest deforestation and degradation that occurred between 1972 and 2002. The term ‘potential change’ refers to the per cent of 1972 rainforest area that was deforested or degraded by 2002, in addition the area of unlogged commercially accessible forest located inside designated logging concession areas. In turn, those areas of loggable, but unlogged forest in designated concessions were separated into two categories, termed allocated and unallocated, on the basis of whether they were already inside active logging concessions. In this regard, potential change estimates the possible outcome of current Government of PNG forestry policies (Overseas Development Institute 2006), but does not include estimates of future non-forestry-related change nor the impact of new forest concessions.

RESULTS AND DISCUSSION

Overview of rainforest change in biogeographic regions and climatic zones

The distribution of total forest change, degradation, net deforestation and potential change across climatic zones and biogeographic regions is presented in Figure 3. Statistics describing these parameters in each of the bioregions and bioclimatic zones are presented in Tables 4 and 5, respectively. A full breakdown of these statistics described via biogeographic region and bioclimatic zone and their intersection into the 81 biomes is available in Table S1.

The greatest per cent of degradation and deforestation has occurred in the lowland forests of coastal regions. The lowlands of New Britain and New Ireland...
Fig. 3. A. Total rainforest change (deforestation and degradation); B. Deforestation; C. Degradation; D. Potential forest change. Each climatic zone in each biogeographic region is coloured by the percentage of forest that was either cleared or degraded 1972–2002, or that was unlogged accessible forest allocated to the forest industry. Shades of green represent 0% potential forest change (dark green) to <10% change (pale green). The yellow to red colour range represents 10% (pale yellow) to 20% (medium orange) to 30% (red) change. The red to purple colour range represents 30% change (red) to 60% (medium purple) change. The purple to grey colour range represents 60% (purple) to 70% (light grey) to 90% (dark grey) change. Areas that were not rainforest in 1972 are shown in white.

Table 4. Areas of primary rainforest in 2002, secondary forest in 2002 (degraded), net deforestation 1972–2002 (Defor.), allocated and unallocated, unlogged primary forest in 2002 (Log. Pot. Unall.) are listed according to their presence in each bioregion.

<table>
<thead>
<tr>
<th>Bioregion</th>
<th>Rainforest area (ha)</th>
<th>% of total</th>
<th>Degraded (ha)</th>
<th>% Degraded</th>
<th>Defor. (ha)</th>
<th>% Defor.</th>
<th>Log. Pot. Tot. (ha)</th>
<th>% Log. Pot. Tot.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sepik–Markham</td>
<td>5 199 008</td>
<td>18.32</td>
<td>354 597</td>
<td>12.13</td>
<td>963 702</td>
<td>18.18</td>
<td>1 996 100</td>
<td>22.85</td>
</tr>
<tr>
<td>Fly–Gulf</td>
<td>6 673 524</td>
<td>23.51</td>
<td>893 485</td>
<td>30.57</td>
<td>755 627</td>
<td>14.25</td>
<td>4 103 553</td>
<td>46.98</td>
</tr>
<tr>
<td>Central Highlands</td>
<td>5 178 012</td>
<td>18.25</td>
<td>7 337</td>
<td>0.25</td>
<td>860 971</td>
<td>16.24</td>
<td>211 745</td>
<td>2.42</td>
</tr>
<tr>
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have been particularly heavily degraded through logging, while the upland regions in these provinces, as well as some upland locations in the Owen Stanley Ranges and Mt Bosavi underwent the least deforestation and degradation. The northern lowlands in Madang, Morobe and the East Sepik provinces have been heavily deforested or degraded, as have the southern lowland and low-rainfall rainforests in Western Province. Lowland forests across the country have the greatest potential change, with 80–90% of lowland rainforest area in New Britain and New Ireland provinces in the Southern and Northern Bismarck regions potentially deforested or degraded.

Forest change in temperature/altitude zones

Lowland rainforests underwent the greatest amount of change, with 30.1% of their area cleared or degraded between 1972 and 2002 (Fig. 4). Lowland forests also have the highest per cent of potential change, approximately 67%, with most of this occurring in the Fly–Gulf and Sepik–Markham regions. The large difference between potential change in the lowland forests (67%) and that in the lower montane forests (17.5%) and upper montane forests (12.9%), as well as the disproportionately large per cent of actual change in the lowland forest, indicates that the lowland forests have been and will continue to be preferentially targeted for commercial logging, plantation development as well as undergoing substantial subsistence-related clearance.

The large per cent of change due to degradation (51%) that has occurred in the lowland forests is simply a consequence of their appeal to the logging
industry. The largest per cent of degradation and overall change in lowland rainforest has occurred in the North and South Bismarck regions. These regions contain the island provinces of East and West New Britain and New Ireland, where the oldest logging concessions are located and where timber resources are close to being fully exploited (Shearman et al. 2009).

The magnitude of the change occurring within lowland forests is of concern given that it is the lowland forests that comprise the majority (65%) of PNG’s forest estate. Our estimate that 67% of the largest forest area in PNG could potentially be degraded or cleared, and the estimate that 30% has already been deforested or degraded, underlines the magnitude of the forest management issues facing the country.

In total, 12.7% of lower montane forests were cleared (12.3%) or degraded (0.4%); however, there was considerable variation across biogeographic regions. Lower montane forests in those regions that achieve higher altitudes or contain a more substantial highlands component – the Owen Stanley Ranges, the Huon Peninsula and the Central Highlands – underwent greater change compared with lower montane forests in the islands or less densely populated Fly–Gulf or Sepik–Markham regions. Lower montane forests generally occur in rugged mountains surrounding intensively settled valleys, and the provinces with the highest population densities occur in the highlands rather than the islands and lowland coastal regions. Lower montane forests underwent less degradation than lowland forests because of the smaller area available for logging activity. High population densities were associated with the largest subsistence clearances (Shearman et al. 2009). Thus lower montane forests in the provinces with higher population densities, the Central Highlands, Huon Peninsula and Owen Stanley Ranges, underwent the greatest change compared with less densely populated Fly–Gulf, Sepik–Markham and island regions, largely as a consequence of their higher human population.

Upper montane forests are found in four biogeographic regions: the Central Highlands, Huon Peninsula and Adelbert, Owen Stanley Ranges and the Bowutu Ultrabasic Belt. Although upper montane forests are relatively free from high-intensity land use practices they have not escaped substantial change. Nationally, between 1972 and 2002, 12.7% of upper montane forests were deforested. This result was unexpected because, unlike the lower montane and lowland forests, the upper montane forests are not used for subsistence agriculture or logging (with the exception of some logging on Mt Giluwe) – the two largest drivers of deforestation and degradation (Shearman et al. 2009). From a conservation perspective this result is important. As the area of upper montane forests is small, it suggests that these forests are under greater absolute threat than those at lower altitude. An example of this loss in the Finisterre Ranges is presented in Figure 5.

High-altitude forests and grasslands are sources of wild food, especially when crops fail because of drought and associated upland frosts. High-altitude grasslands in PNG are relatively flammable and especially during droughts, fires ignited by humans or lightning have been recorded spreading into adjacent forests, causing the death of trees (Pajjmans & Loffler 1972). In many areas loss of upper montane forest was clearly associated with fire, and it is apparent that fire lit by people, especially during El Niño years, was the major cause of this change. We conclude that fire in the upper montane zone, especially during El Niño years, such as 1997–1998, but also during 2002, has resulted in the encroachment of grassland and scrub into many previously forested areas.

Rainforest change in rainfall zones

Deforestation was negatively correlated to rainfall in that a greater proportion of low-rainfall forest was cleared compared with moderate- and high-rainfall forests, and a greater proportion of moderate-rainfall forests were cleared compared with high-rainfall forests. This may reflect a higher regenerative capacity of high-rainfall forests, or that these areas occur in more rugged mountainous areas so are more resistant to human incursion for secondary reasons. It is also likely that low-rainfall forests are more vulnerable to conversion as a consequence of fire than are wetter forests (Lewis 2006). As dry weather greatly increases the risk of fire, it is low-rainfall rainforests that are at most risk of conversion especially when they undergo disturbance from logging or gardening activity. Indeed the largest area of deforestation due to fire occurred in Western Province in low- and moderately low-rainfall zones.

Degradation from logging activities was positively correlated to rainfall reflecting the concentration of logging activity in the forests of New Ireland, East and West New Britain and Manus that are located primarily in the highest-rainfall zones. High-rainfall lowland forests tend to yield a higher timber volume per hectare (Vanclay 1992; Bruijnzeel & Veneklaas 1998) and the island provinces of New Britain, New Ireland and Manus have also been readily accessible to the logging industry compared with mainland or highland forests. Both accessibility and profitability may have therefore contributed to the targeting of lowland high-rainfall forests in the island provinces for logging, resulting in the increased per cent of degradation with increased rainfall. The high-rainfall montane forests
have been too inaccessible to sustain significant commercial logging.

**Rainforest change in biogeographic regions**

Both degradation and deforestation varied considerably across and sometimes within the biogeographic regions of PNG. The largest per cent of total change tended to be in the east of PNG in the islands and lowlands in the Bismarck, D’Entrecasteaux, East Papuan Islands and South-East Papua–Oro region. The only region with a significant highlands component to undergo deforestation at a comparable magnitude to the islands and lowland regions was the Huon Peninsula and Adelbert region.

**Southern and Northern Bismarck Island Arc.** The forests in the Southern and Northern Bismarck Island Arc regions had by far the largest per cent of change with 45.5% and 42.9% of forests cleared or degraded between 1972 and 2002, respectively. Logging has been the major driver of change in this region with the majority occurring in lowland areas. This is because the coastal lowland forests in the Bismarck Islands are accessible to commercial logging, whereas upland forests, mostly restricted to the karstic Whiteman and Nakanai Ranges, are not.

**D’Entrecasteaux Islands.** The D’Entrecasteaux region possesses only a very small per cent of PNG’s forest cover (0.4%) but had the highest proportion of deforestation (28%) of all the biogeographic regions. The loss of these forests could impact heavily on the endemic species found in this region. There was very little difference between potential forest change and actual forest change indicating that little, if any unlogged forest has the potential to be allocated to the logging industry.

**Fig. 5.** The upper Nankin catchment in the Finisterre Ranges (3400 m). This area was almost entirely forested as recently as 1995. Fires, probably during the 1997–1998 El Niño period, deforested a large area in this mountain range. Some remnant forest can be seen in the wetter gulleys. Dead trees can be seen on some of the ridgelines and foreground. Regeneration of woody vegetation is largely absent.
As was the case across PNG, most forest change and deforestation in the D’Entrecasteaux Islands occurred in the lowland forests. Within the lowlands, low-rainfall forests underwent both the most change and the most deforestation. This is because higher-rainfall areas in these islands tend to be steep and comparatively inaccessible.

**Huon Peninsula and Adelbert Ranges.** The Huon Peninsula and Adelbert region had the third highest proportion of forest cleared (22%) of all biogeographic regions. In the montane forests there was little degradation because of logging, and in the lowland forests the per cent of forests degraded because forestry was relatively small. However, as was the overall pattern of forest change, the highest per cent of degradation due to logging occurred in the high-rainfall forests.

**East Papua Islands.** The East Papua Islands had the fifth largest proportion of forest cleared or degraded between 1972 and 2002. Logging has been an important driver of change in the East Papua Islands region. Over half of the entire area of Woodlark Island, which makes up most of this region, has been allocated to the logging industry.

**Sepik–Markham, Fly–Gulf and South-East Papua–Oro.** Consistent with the overall pattern of forest change, the South-East Papua–Oro, Fly–Gulf and Sepik–Markham regions showed increasing degradation with increased rainfall and increasing deforestation with decreasing rainfall. The South-East Papua region, unlike the Sepik–Markham and Fly–Gulf regions, had comparatively high proportions of forest cleared. The South-East Papua–Oro region had a greater proportion of total forest change as a result of logging-related forest degradation than did the Sepik–Markham and Fly–Gulf regions. This is because the forests have a much greater proportion of forests within logging concessions and have a larger number of logging concessions that have been operating over a longer time period (National Forest Service 2000). Thus the South-East Papua–Oro has undergone proportionally more clearance and degradation as a result of logging than have the Sepik or Gulf biogeographic regions.

**Ultrabasic Belt, Central Highlands and Owen Stanley Ranges.** The regions with the lowest proportion of forest change were the Ultrabasic Belt, the Owen Stanley Ranges and the Central Highlands and all three regions suffered only a very small amount of commercial logging. As both the Central Highlands and the Owen Stanley Ranges are located in the most rugged and mountainous terrain, the comparatively low per cent of forest degradation in these regions is due to their inaccessibility. In the case of the Ultrabasic Belt, this region has relatively low forest biomass and productivity and may therefore be of less value for both forestry and agricultural purposes, and hence underwent relatively little change despite being relatively accessible.

The Owen Stanley Ranges biogeographic region is distinctive in the high per cent of change that has occurred in the lower montane, high-rainfall forests. These forests have been particularly affected by high-altitude burning. The lower montane rather than upper montane forests in this region may have undergone a greater proportion of deforestation as a result of fire because mountains in this region are isolated and coastal. Altitudinal zonation of vegetation has been shown to occur at lower altitudes in isolated coastal mountains, a phenomenon known as the ‘Massenerhebung Effect’ (Richards 1952). Thus the ‘upper montane’ vegetation may be located at a lower altitude in the Owen Stanley Ranges, and hence was strongly impacted by grassland burning.

Both the Central Highlands and Owen Stanley Ranges had the lowest potential forest change, reflecting the large per cent of forests in this region that are inaccessible and therefore unlikely to be allocated to the logging industry. The Ultrabasic Belt in contrast, had a much higher proportion of potential forest loss because of the comparative accessibility of forests in this region. Despite being relatively unattractive for logging because of the low timber biomass, the comparative accessibility of forests in the Ultrabasic Belt may lead to future clearance and degradation.

**Rainforest change in protected areas**

The current national protected area system comprises a total of 34 terrestrial wildlife management areas (WMAs) and National Parks that have been formally gazetted, covering just 1.29 million hectares or 2.8% of PNG’s total land area. In 2002, these protected areas included a total of 542,166 ha of rainforest, 54,332 ha of swamp forest and 8892 ha of mangroves. This area of forest represents 1.9% of the total rainforest estate as well as 1.6% of the swamp forest and 1.5% of the mangroves. As these low numbers indicate, establishment of protected areas has not been a smooth process. Over a third of existing protected areas were gazetted in the first 4 years of Independence (1975–1979). In the subsequent 23 years only 15 more were declared. A comprehensive review in 1992 found that, even without any promotion or publicity of the scheme, a backlog of 120 proposals from landowners for assistance from Department of Environment and Conservation (DEC) to establish WMAs had accumulated (Hunnam 1992). In the past

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13 years, only seven new WMAs have been established and all have come about through major efforts by non-government organizations, with little support from government. It is also relevant to note that the national government recently imposed a moratorium on the ratification of new protected areas in order to negate the potential for conflict with the allocation of potential logging areas to the timber industry, under the government’s ‘export-driven’ economic policy (Shearman et al. 2008).

Over the 1972–2002 period, a total of 11 951 ha (2.2%) of the gazetted rainforest has been degraded through logging, and an additional 38 927 ha (6.7%) was cleared, mostly by subsistence activities. It was found therefore that rainforests within protected areas had experienced an overall change of 8.9% during the study period. While this suggests that forests within protected areas are better protected than forests overall, which had a country average of 24% change (Shearman et al. 2009), the wide variation in the change that occurred in WMAs indicates this is misleading: six protected areas had no forest change but another six had more than 50% of their 1972 forest area cleared or degraded, and four had 99% of their extent deforested or degraded by 2002 (Table S2). A further 16.0% of rainforest within protected areas has been allocated for logging.

The majority (77%) of forest in the protected area system is enclosed within two WMAs: Hunstein WMA in East Sepik Province (160 850 ha) and Crater Mountain WMA that straddles East Highlands, Chimbu and Gulf Provinces (255 306 ha). On account of their low population density and inaccessibility, both WMAs experienced relatively little forest loss (2% in Hunstein and 3% in Crater Mountain). If all other 32 WMAs are considered separately from Hunstein and Crater, then the results of the change analysis present a radically different picture of the effectiveness of conservation designation. In these 32 WMAs, a total of 126 010 ha (77%) of forest remain, while 23% of their 1972 extent has been cleared or degraded within the study period. This indicates that for the majority of WMAs, there is no discernable difference in the rate of change because of their conservation status.

With regard to the bioregional distribution of protected areas, it was found that only one biogeographical region had more than 5% of its forests within a protected area. This occurred in the D’Entrecasteaux Islands where the total forested area, both within and outside of protected areas, represents only 0.4% of PNG’s forests. The East Papua Islands region had no forests in protected areas, and the Owen Stanley (0.03%) and South-East Papua–Oro (0.07%) regions had virtually no rainforests within protected areas.

Further underlining the inadequacy of WMAs as a means of conserving forest in PNG is the finding that only 37 of PNG’s 73 forested biomes were represented in protected areas. Only 6 out of the 73 biomes had 10% or more of their area contained in a protected area. In addition, the protected area network contains almost no upper montane forests. The lowland forests, which underwent the most deforestation and degradation also have little representation in protected areas.

Several forest areas within WMAs have been almost completely deforested. These include the low-rainfall lowland forests contained in WMAs in the South-East Papua–Oro region, and the high-rainfall lowland forests contained in WMAs in the Huon Peninsula and Adelbert region. Similarly, seven of the lowland forest types contained in WMAs within the South-East Papua–Oro, Huon Peninsula and Adelbert, Central Highlands, Sepik–Markham and Southern Bismarck Islands regions had more than 65% of their extent deforested or degraded. This pattern of change, with lowland forests in WMAs generally undergoing the highest proportion of deforestation or degradation, is consistent with the overall forest change pattern in PNG.

It is also apparent from these results that commercial logging has been occurring within protected areas. Three of the WMAs in New Britain have been partially logged as has Mojirau WMA in East Sepik. Mojirau WMA was the first protected area to be designated in the country. In addition, large areas of existing protected areas have been allocated to the logging industry – approximately 18.4% of their total area in 2002 – much of which is potentially loggable forest (16%).

The network of protected areas, according to the United Nations Convention on Biological Diversity, to which PNG is a signatory, was intended to be ‘representative of biological diversity’ (Prescott et al. 2000). The results of this analysis strongly suggest that the current system of protected areas is ineffective on a number of levels. The WMAs contain only a very small proportion of PNG’s forest estate, and this area is disproportionately located in the lower montane forest zone, a zone that has been least affected by logging and subsistence clearance. The WMA network does not contain representative examples of forest types in the various bioclimatic and bioregional zones. Furthermore, outside of the Crater and Hunstein WMAs, the other 32 WMAs are experiencing clearance and degradation at rates comparable with the rest of the country. The fact that large areas of some WMAs have been logged and much has been allocated to the logging industry, serves to emphasize the point that management of these areas has not been taken seriously by the Government of PNG. Given that the last decade has seen little expenditure of Government funds on the site management of these areas (Chatterton et al. 2006), while in some cases actively promoting their degradation through their allocation to the logging industry, this can hardly come as a surprise.
CONCLUSION

Despite the fundamental significance of PNG’s forests to the country’s ecology and the future of the great majority of its citizens, our findings of substantial deforestation and degradation across biomes and both in and outside of protected areas, indicate that there have been no coherent efforts to protect or sustainably manage the country’s forest estate.

For many, the integrity of its diverse forests, ecology, tribal cultures and endemic flora and fauna make conservation an imperative. As ecological knowledge has improved and been shared over recent decades, the essential grounds for conservation have been increasingly recognized both internationally and locally (Brooks et al. 2006; European Union 2006; Rudel 2008; Grainger 2009). There has, however, been little progress in PNG over the past decades towards a vision that might be shared between the major stakeholders involved – governments, landowners, resource developers, conservationists and local communities.

Those seeking or advocating conservation and a sustainable future need to be much clearer about their vision and objectives: to what extent should natural values be conserved and at what constraints to development? What limits should be imposed on logging, forest clearing, plantation development, quarrying and mining minerals? What resource-based industries would best support the rapidly increasing rural population and their economic and social development? For their part, resource developers appear unwilling to accept limits to access to resources. Many new mines are planned and despite PNG’s international calls for support to protect its forests, forestry concessions continue to be allocated (Shearman et al. 2008). In the recent past approximately one million hectares of forest have been allocated to agriculture development projects, meaning that they can now be clear felled. Our findings show that all parts of the country have been considered open to exploitation, even within gazetted nature reserves. Achieving a balance between conservation and development has been challenging.

It is questionable that the increased revenue from natural resource extraction has produced equivalent increases in health, education services and infrastructure development. If it has not, what measures can be put in place to guarantee that further natural resource extraction will result in positive outcomes for the majority of Papua New Guineans?

Clearly, current forest conservation efforts are neither adequate or effective. Conservationists have been driven too much by the conventional approach of protected areas, funding fads and a narrow determination to safeguard ‘the best bits’ (Kaimowitz & Sheil 2007; Cameron et al. 2008). The past 30 years have shown that management of natural resources for conservation and development has to be comprehensive and integrated if it is to achieve its multiple balanced aims effectively in the long term (Grainger & Konteh 2007; Kaimowitz & Sheil 2007; Rudel 2008). Site-based conservation of nature is an important strategy but one that that remains to be properly implemented and supported in PNG. Strengthening the WMA system and then providing appropriate support for the many hundreds of applications from groups of customary landowners could be done immediately, easily and at modest cost. This should be given the highest priority. Despite the system’s neglect, the WMA remains a suitable starting point for creating local resource management areas dedicated to multiple sustainable uses. Such a scheme could be developed countrywide, readily and rapidly, to create an effective system that is applicable and accessible to virtually all landowner groups across the country.

Fundamentally however, it is doubtful that the notion of ‘setting aside’ 10% or 20% of the land area for conservation is a useful or desirable objective for PNG, despite its appeal to prioritization exercises and indeed industrial developers (Kaimowitz & Sheil 2007; Cameron et al. 2008). The outcome of the past 30 years of conservation and development efforts suggests that an inverse target may be more meaningful and appropriate: to zone 90% of the land for conservation, in the sense of judicious and integrated use of the country’s natural resources. Inverse zoning would indicate that with additional safeguards the country might be able to afford to degrade up to 10% of its terrestrial ecosystems without reducing the natural values and ecosystem functions of the remaining majority. The principal value of such a target would be to stress that much more attention needs to be given to the management of resource uses – for forestry, agriculture, mining, fishing, urban settlements and infrastructure – to ensure that their impacts on natural values are reasonable and acceptable. The need to adequately prescribe and build institutional capacity to govern ecologically sustainable development and integrated use of natural resources is therefore major area in which both conservationists and the PNG Government need to concentrate their efforts.

As a country that is by all standards heavily forested, possessing a low population and huge mineral deposits, if it is not possible for the PNG, with the assistance of the international community, to achieve long-term protection of large areas of forest, then it seems unlikely that it can be achieved anywhere on the planet.

ACKNOWLEDGEMENTS

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Fig. S1. Principle structural geological features of Papua New Guinea (derived from Ollier & Bain 1972).

Fig. S2. Geological map showing the Australian craton (grey), the New Guinea orogen (between the heavy broken lines) and the accreted New Guinean terranes (black). The islands north of New Guinea (Manus, New Ireland, New Britain and Bougainville) comprise Palaeogene and Quaternary volcanic arcs (Heads 2001a).

Fig. S3. Forest zones as defined in the Forest Inventory Mapping System (Hammermaster & Saunders 1995).

Fig. S4. The location of designated wildlife management areas (WMAs) and National Parks (NPs) in Papua New Guinea (PNG).

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Table S1. Forest extent, change and logging potential in biogeographical regions and bioclimatic zones. 1972–2002 summary statistics.

Table S2. The area of vegetation types and forest change (1972–2002) in PNG’s WMAs and NPs, ranked by size.

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Supplementary Figure 2. Geological map showing the Australian craton (grey), the New Guinean orogen (between the heavy broken lines) and the accreted New Guinean terranes (black). The islands north of new Guinea (Manus, New Ireland, New Britain and Bougainville) comprise Palaeogene and Quaternary volcanic arcs (Heads, 2001a).
Supplementary Figure 3. Forest zones as defined in the Forest Inventory Mapping System (Hammermaster and Saunders, 1995).
Supplementary Figure 4. The location of designated WMAs and National Parks (NPs) in PNG.

1 = Tonda WMA; 2 = Crater Mt WMA; 3 = Hunstein WMA; 4 = Kamiali WMA; 5 = Oia Mada Wara WMA; 6 = Lake Kutubu WMA; 7 = Lihir WMA; 8 = Bagiai WMA; 9 = Ranba WMA; 10 = Siwi Utane WMA; 11 = Poliki WMA; 12 = Garu WMA; 13 = Majirau WMA; 14 = Ndrolowa WMA; 15 = Klampun WMA; 16 = Jimi Valley WMA; 17 = Iomare WMA; 18 = Lake Lavu WMA; 19 = Neiru WMA; 20 = McAdams NP; 21 = Crown Island WMA; 22 = Varirata NP; 23 = Mt. Nuserang WMA; 24 = Zo-Iomage WMA; 25 = Tavalo WMA; 26 = Mt Kaindi WMA; 27 = Sawataetae WMA; 28 = Mt Wilhelm NP; 29 = Balek WMA; 30 = Mt. Galvisuka WMA; 31 = Hambareta WMA; 32 = Mt Susu WMA; 33 = Namanatabu WMA; 34 = Nanuk WMA
All areas are recorded in square kilometers. Areas of Primary Forest in 2002 (F), Secondary Forest in 2002 (Degraded), Net Deforestation 1972-2002 (Loss), Allocated but unlogged Primary Forest in 2002 (Log. Pot. All) and Unallocated, unlogged Primary Forest in 2002 (Log. Pot.Unall) are listed according to their presence in each Biogeographical region and Bioclimatic Zone. The parameters used to define each of the Bioclimatic Zones are described in Table 5.
Supplementary Table 2. The area of vegetation types and forest change (1972-2002) in PNG’s WMAs and NPs, ranked by size.

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