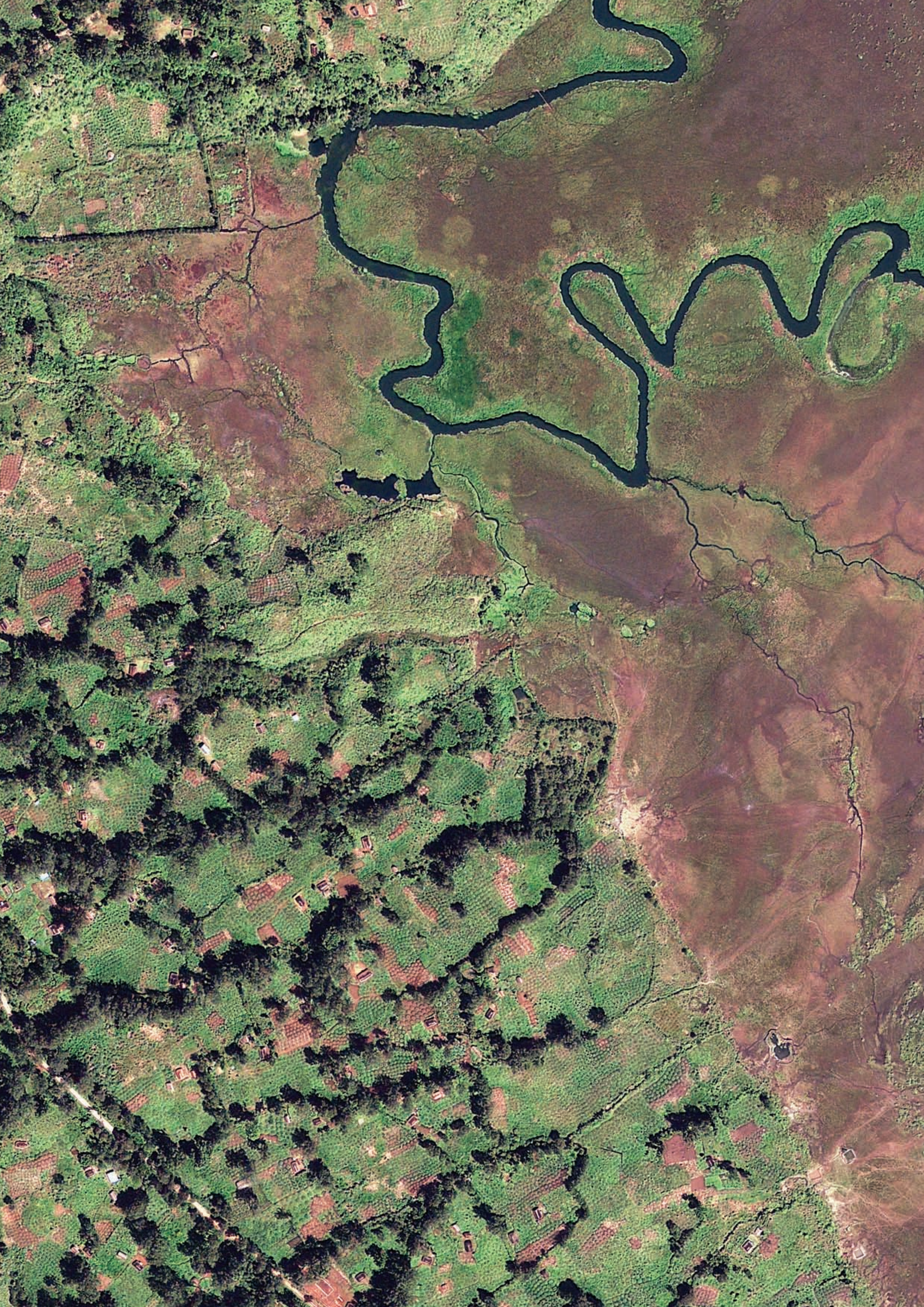
The State of the Forests of Papua New Guinea 2014

Measuring change over period 2002-2014

UPNG
Remote Sensing Centre


Southern Highlands



Lake Murray

Kamula Doso, Western Province

In memory of Commander William H. McGrath

Published by the University of Papua New Guinea, Port Moresby, Papua New Guinea.

This document has been produced with the financial assistance of the European Union. The contents of this document are the sole responsibility of UPNG Remote Sensing Centre and can under no circumstances be regarded as reflecting the position of the European Union.

Acknowledgements:

The authors would like to thank the following individuals whose support for this work was instrumental in its completion; The University of Papua New Guinea, The European Delegation in Papua New Guinea, The Hon. Martin Dihm, Prof. Albert Melam, Prof. Peter Petsel, Clement Bourse, Professor Jamie Kirkpatrick and Dr Greg Asner,

Bibliographic reference:

Bryan, J.E., Shearman, P.L. (Eds). 2015. The State of the Forests of Papua New Guinea 2014: Measuring change over the period 2002-2014. University of Papua New Guinea, Port Moresby.

Institutional affiliations:

Jane E. Bryan *, ‡, Phil L. Shearman *, †

* UPNG Remote Sensing Centre; University of Papua New Guinea, Port Moresby, Papua New Guinea;

† Research School of Biology, the Australian National University, Canberra, Australia, 0200;

‡ Geography & Environmental Studies, School of Land and Food, University of Tasmania, Hobart, Tasmania, Australia, 7000

University of Papua New Guinea Remote Sensing Centre (http://www.rsc.upng.ac.pg):
The University of Papua New Guinea Remote Sensing Centre is a teaching and research facility concerned with land-cover and land-use in Papua New Guinea.

ISBN: 978-9980-89-106-8

Design and typesetting by Kathleen Kovea
PO Box 1035, Port Moresby,
Papua New Guinea.
Printed by Birdwing PNG Ltd.

Contact: UPNG Remote Sensing Centre,
PO Box 320, University,
NCD, Papua New Guinea.
Email: upngrsc@ozemail.com.au

Cover image: Sunset from Mt Yule

The State of the Forests of Papua New Guinea 2014

Measuring change over the period 2002-2014

Milne Bay, Samarai Region

Foreword

For those who have walked the high country forest, felt the moss beneath their feet and breathed the clean mountain air of the highlands, the memory never fades. And for those who have experienced the rich tropical rain forests and lowland humidity, the memory is one of awe before the ancient and majestic trees, knowing that we humans are only temporary in the realms of mighty nature. For many of us these encounters become memories, but for others in Papua New Guinea it is day to day life.

I write this foreword whilst attending COP 21 in Paris. Waiting for the world to negotiate a path forward that ensures the survival of many small island nations of the Pacific from the worsening effects of climate change. Forest resources are not only beautiful, but in this context they are vital, as they link the atmosphere and carbon dioxide emissions to our very survival on Earth.

The science of Forests and the science of climate and oceans are inextricably related and interconnected. We as humans fit in there as both beneficiaries and manipulators of an architecture that we are still discovering. The interconnection of Forest carbon and the impact and change in weather patterns, moisture, rain, winds and climate are connected with ocean carbon sea level rise, ocean acidification, coastal flooding, and changes in ocean temperatures. All are now critically balanced at a time of great uncertainty for the future of our one home, this remarkable island in space - Earth.

So where and how do the Forests of Papua New Guinea fit into this equation? This profound and in depth work by dedicated individuals pulls together years of research and data to present us with a scientific analysis of the state of Papua New Guinea's Forests. At the heart of this work are the fundamental questions of how far can we push the limits of commercial logging within the current management systems, and what are the implications of seriously compromising the health of the country's forest.

The authors in this book seek to provide their responses to the following questions.

What is the real stock of the Forest resource? Does the current management system further degrade a resource that is vital to the natural health and wealth of our Nation and the planet? In what way will the choices made today determine the consequences for the environmental wealth of our country in the future? How critical are those choices in determining the future, and in what time frame? What of mitigation modalities, and how can such systems hold off the harvesting of our Forests?

Forests are politics, Forests are wealth, Forests are business, Forests are development, and most fundamentally Forests are a life support system connected to other variables that help sustain life on Earth. Papua New Guinea holds the largest contiguous area of forest in Asia - Pacific and the third largest tropical rainforest on the planet. It is the richest forest of the Pacific and it holds a bounty of incredible rich and complex biodiversity. The development challenges for Papua New Guinea emphasise the extraction of our natural resources and the opportunity to be economically self-sufficient. As citizens we accept this rationale, but we ask at what cost now and for the future.

The recent years have seen the deep divisions in our community around the permitting of logging and management of our Forest resources. Legal battles have seen civil society and communities pitted against government. The challenge before us with the onslaught of Climate change is to now hold Government to account on the promise made at COP 21. The undertaking that millions of hectares of forests will be set aside for the REDD plus initiative and hundreds of thousands of hectares will be reforested. This is a clear and valuable promise that our country has made before the international community and one where we, uniquely as a nation, have in place the legislative frame work to combat climate change. Now we need the Political will to join with the Administrative challenges to bring this to bear, for our children and grandchildren, and for our home Papua New Guinea, and the planet Earth.

Dame Meg Taylor
Secretary General, Pacific Islands Forum, Fiji

Preface

Massive changes are afoot in the World's ecosystems. Humans are warming the climate system to a degree that threatens our survival by burning fossil fuels and clearing and logging ever more forest. Even the most remote regions of the globe now see the relentless encroachment of agribusiness and logging. In the tropics, the ongoing loss and damage of natural forest, and their replacement with croplands, pastures, and vast timber concessions, is truly now a global issue. One of the largest remaining areas of tropical rainforests remaining, some 28 million hectares, is found in Papua New Guinea. While in recent decades this nation has seen significant deforestation and forest degradation, when compared with other nations, much of PNG's forests remains relatively intact.

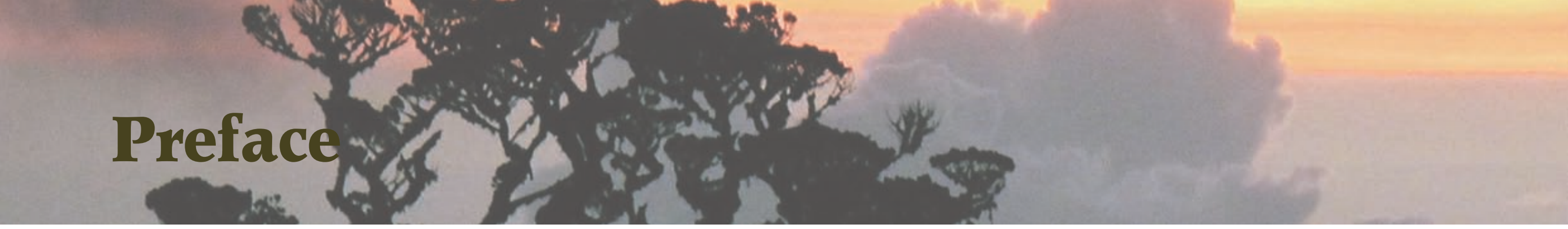
Papua New Guinea is a south pacific nation located between Indonesia and Australia. It has a rugged mountainous interior surrounded by extensive flatter lowlands reaching to the coast. The flora and fauna found in PNG's forests are some of the most diverse and unique in the World. The citizens of PNG rely heavily on these forests. Vast quantities of carbon are also stored in PNG's forests while they remain standing, but clearing or logging results in substantial releases of this carbon into the atmosphere. Not only are PNG's forests ecologically significant, they have also become central to the politics of global climate change. The Government of PNG has been at the forefront of campaigning to have the Reduced Emissions from Deforestation and Forest Degradation (REDD) initiative included in the United Nations climate change protocols. REDD would potentially mean that tropical nations may be compensated for preventing deforestation and degradation within their borders.

Given the ongoing crisis of tropical deforestation, and the increased political significance of PNG's forests, it has never been more important to understand in detail what is happening to these forests. The University of Papua New Guinea Remote Sensing Centre (UPNG RSC) has spent the last decade collating and processing satellite imagery and honing mapping techniques for PNG circumstances. As a result UPNG RSC has been able to produce accurate and reliable maps of forest in PNG, and to map the extent of clearing and logging.

In 2008, UPNG Remote Sensing Centre (UPNG RSC) published the "State of the Forests of Papua New Guinea" report, which described changes in PNG's forests between 1972 to 2002 at a spatial resolution capable of detecting fine scale and localised changes in PNG's forests. This report documented the loss of 24% of primary rainforest ecosystems in the period 1972-2002. It was able to accurately quantify the two largest causes of this loss: industrial logging and the expansion of subsistence agriculture into previously uncultivated forests, driven by a rapidly increasing rural population.

Since 2002, there have been substantial changes occurring in PNG's forests. In 2013, UPNG RSC undertook to update the State of the Forests Report by measuring the present condition of PNG's forests, and to map the area that has been logged and cleared since 2002. The results of this study are presented in Chapter 1. One of the factors behind recent change has been the allocation of large areas of forest into "Special Agriculture and Business Leases" (SABLs), allowing for their clearance to facilitate agricultural development. There has been substantial debate about whether these leases were genuinely intended for agricultural development, or whether they were a mechanism by which logging companies could access additional land and circumvent PNG's forestry laws. In Chapter 1, the first detailed mapping of forest change that has occurred inside SABL's 2002 to 2014 is presented. Chapter 1 also contains a summary of the areas that have been cleared and logged in since 2002 and a discussion of the estimated volume of remaining timber stocks. Re-entry logging of PNG's forests well short of the designated 35 year cutting cycle has been a problem in some of PNG's logging concessions, and an overview of this issue with a case study from the Wawoi Guavi concession is presented. The UPNG Remote Sensing Centre has recently developed an automated system to monitor forest fires in PNG (http://fire.pngsdf.com). The relationship between fires detected in PNG's forest and deforestation and logging measured over the period 2002-2014 is also examined.

The 2015 State of the Forests of PNG report includes summaries of recent scientific developments of particular relevance to PNG's forests. These are written by local and international experts in their field. Over the period 1972 to 2014, an important and emerging threat to PNG's forests has been climate change. It has become unequivocal that global climate system is warming, and this has major implications for PNG's forests. In Chapter 2, Professor Will Steffen from the Australian National University provides a detailed summary of our current knowledge of climate change science, and how PNG is, and is likely to be, impacted by these trends.



Preface

In the last decade there has been an increasing understanding of the role of tropical forests in the energetics of global climatic and regional weather patterns. In Chapter 3 Dr. Anastassia Makarieva and Dr Victor Gorshkov of Petersburg Nuclear Physics Institute present the latest atmospheric research on how PNG forests contribute to the maintenance of favorable climatic regimes and examine how their continued deforestation and degradation could trigger adverse changes in the local, regional and possibly global climate.

The New Guinea Binatang Research Centre is at the forefront of insect and forest research in PNG. In Chapter 4 the director, Dr Vojtech Novotny, and deputy director, Pagi Toko describe what is currently known about arthropods biology and diversity in PNG, and provide a summary of their recent research, including data from the unique permanent forest dynamics plot at Wanang.

The forests of Papua New Guinea support some of the richest assemblages of vertebrates on the Planet. They are home to least 1786 species of amphibians, reptiles, birds and mammals. In Chapter 5, Professor Allen Allison of Bishop Museum, and Oliver Talowin of Tel Aviv University outline what is currently known about the diversity of PNG vertebrates, and how deforestation and logging are likely to impact these biota.

Orchids are an ancient plant family, and PNG is a major centre of orchid diversity. In Chapter 6, Dr. Ed de Vogel of Naturalis Biodiversity Center, in The Netherlands, provides an overview of what is known about orchids in PNG. Major threats to Papua New Guinea orchids come from two main sources, the destruction of habitat and over-collecting of certain species.

PNG is a tropical country located in a region of active volcanism, and has a complex climatic and geological history. These are some of the factors that have shaped a unique flora. In Chapter 7, Professor Osia Gideon of UPNG Division of Biological Sciences outlines the origins and affinities of PNG's plants, and the unique climatic and geological events that have produced them.

New Guinea is one of a relatively small number of places around the world where new species of mammals are still discovered on a regular basis. In Chapter 8, Dr Ken Aplin from the Division of Mammals of the U.S. National Museum describes the history of mammal research in PNG, as well as outlining exciting recent discoveries.

Finally, maps showing forest extent in 2014 and the location of changes measured between 2002-2014 for each province are presented in Chapter 9.

Contents

Chapter 1

The current state of PNG's forests and changes between 2002 & 2014

Jane Bryan[1,2], Phil Shearman[1,3], Geraldine Aoro[1], Freesia Wavine[1], Jane Zerry[1]

[1] UPNG Remote Sensing Centre; University of Papua New Guinea, Port Moresby, Papua New Guinea.
[2] Geography & Environmental Studies, School of Land and Food, University of Tasmania, Hobart, Australia.
[3] Research School of Biology; The Australian National University, Canberra, Australia.

Summary of the main findings

The 2014 State of the Forests report documents substantial changes in PNG's forests over the period 2002-2014. The main driver of this change was the industrial logging industry both through the degradation of primary rainforest to secondary logged forest, and the conversion of forest to other non-forest land cover types such as cleared land and scrub.

The most significant findings of the study are:

- In 2014 there were 278,767 km^2 of closed canopy rainforest in PNG, 13% of which had been logged at least once since 1972. Since 2002, 4.1% of forest was cleared or logged. A total of 3752 km^2 of rainforest was deforested and 7705 km^2 of previously unlogged forest was degraded through logging. Overall PNG's forests were being cleared or degraded at a rate of 0.49 % per year in 2014, a deceleration compared to the 1972-2002 period.
- Those forests accessible to the logging industry underwent much greater change. Between 2002 and 2014, 7.3% of commercially accessible forests were logged or cleared – much greater than the 4.1% that was cleared or logged overall.
- The island provinces overall saw the greatest proportion of forest change between 2002 and 2014, with Manus having 9.1% of its forests logged or cleared, New Ireland 7.6% and West New Britain 7.5%. However, the period saw substantial changes to the mainland lowland forests. In Gulf province and West Sepik, 7.7% and 6.3% of forests were cleared or logged since 2002. By far the greatest extent of logging occurred in the lowland forests of West Sepik, Gulf and Western provinces.

- In 2014 there was 38,242 km^2 of rainforest inside Special Agriculture and Business Leases (SABLs). The terms of these leases potentially allow for their future deforestation for industrial agricultural developments. Between 2002 and 2014, 2047 km^2 of forest within SABLs was cleared or logged. By far the biggest cause of forest change in SABLs was industrial logging and most of this logging was not followed by clearance to allow for the development of agricultural plantations. However substantial oil palm plantations were created in four SABLs, suggesting that this trend may change in future.

- In 2014, 14.9 million hectares of rainforest occurred inside logging concessions. Out of 228 logging concessions where active logging occurred over the period 1972-2014, 72 had more than 80% of their commercially accessible forests logged by 2014. Most of these were in West New Britain, West Sepik and Western provinces.

- Repeat harvesting within the 35 year cutting cycle prescribed by the PNG Logging Code of practice was widespread inside PNG's older logging concessions. In the Wawoi Guavi concessions of Western province, re-entry logging was observed only 15 years after the first harvest - 20 years sooner than ought to have been the case. A key priority for forest management in PNG is immediately excluding logged forests from re-entry logging in too short a time period.

- In PNG's logging concessions there is an estimated average of 88.1-98.6 million m^3 of timber remaining. In order to maintain logging concessions for timber production into the future and respect the 35 year cutting cycle, annual timber production in PNG needs to be at least 1.6 to 1.8 times lower than current production levels.

- Between 2002 and 2014 there were 81,819 fire hotspots detected in PNG, 76% of which occurred within 6 km of a building. There was no major El Niño events during this period and only 7% of all recorded fires occurred in within rainforest. In 2015 a major El Niño developed resulting in a huge increase in fires – 15% of which occurred in forests, placing these forests at an increased risk of future deforestation.

- The largest remaining expanse of intact lowland forest is located in the Kamula Doso/Strickland region of Western Province. The PNG Government is now progressing this area towards allocation to the logging industry. At the recent UN climate change negotiations in Paris, the PNG Government pledged to prevent logging and clearing in millions of hectares of rainforest as part of its contribution to fighting global warming. By halting the allocation of Kamula Doso, PNG can save 155 million tonnes of CO_2 emissions and immediatly fullfil its commitments. The area of rainforest in Kamula Doso is roughly the same as the entire rainforest area in the Wet Tropics of Queensland, Australia.

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[1] Full details of the methods used to map forest cover and measure change are outlined in Annex 1.

Introduction

The forests of PNG are an ecological wonder and one of the last places in the world where large unbroken expanses of tropical rainforest still abound. However in recent decades there has been an increase in deforestation and logging placing the future of these forests under threat. Given the global and local significance of PNG's forests, understanding where and what changes are occurring within these ecosystems is important. Accurately mapping forests and forest change at a level capable of detecting fine scale clearances and logging requires the use of high resolution mapping. In *The State of the Forests Report 2014*, just such an exercise was undertaken.

The University of Papua New Guinea Remote Sensing Centre (UPNG RSC) measured the extent of land cover types in PNG for the year 2014, as well as changes that have occurred in the area of closed canopy rainforest between 2002 and 2014. Land cover and forest areas were measured using 30 m resolution Landsat 8 satellite imagery that was captured between 2013 and 2015. For convenience hereafter, we refer to this period as '2014'. Changes in forest area that have occurred since 2002 were measured by comparing the new 2014 land cover map with a 2002 land cover map created for the first State of the Forests of PNG report[1].

1.1 Forest definitions

Globally, there are many different ways to define what constitutes a forest and which definition is used will depend on the purpose of the analysis. Mapping forests over large areas is labour and time intensive and requires specialised skills, computer software, and satellite imagery. The more detailed the satellite imagery, the more data intensive, and hence time and labour intensive, the mapping exercise. For those studies that aim to measure global trends using a single methodology, the broadest possible definition of forest is used in order to capture all areas with some form of tree cover. This has the advantage of making comparisons between nations possible, but it has the disadvantage of losing local detail. The United Nations Food and Agriculture Organisation (FAO) definition of forest is perhaps the most commonly used example of one such broad definition. The FAO defines forest as any area 0.5 ha or more in size with greater than 10% canopy cover and trees over, or capable of growing over 5 metres in height. While this definition has the advantage of allowing comparisons across nations, it has a number of limitations for its application in PNG. This issue is illustrated in Figure 2 to Figure 4, in contrast to the definition of forest used in this report that is shown in Figure 1

In the context of PNG, defining forest as an area greater than 0.5 ha with more than 10% canopy cover with trees taller than, or capable of growing taller than 5 meters would mean that many areas of savannah woodland, food gardens and secondary woody scrub are classified as 'forest', when they are ecologically very different (Figure 2, Figure 3, Figure 4). In much of PNG, the largely rural population is sustained by local food gardens which are cleared and planted according to varying regimes of shifting cultivation. This has created, in many locations, a landscape of gardens, secondary woody scrub growing on abandoned gardens, and uncleared forests. If one was to call all three classes 'forest', the total area of forest in PNG may be overestimated. This is because both woody scrub and gardens would be included as 'forest'. It would also mean that the area of deforestation would be underestimated because the replacement of previously uncleared forest with garden would not be detected. In addition, this broad definition of forest means that savannah woodland may also be categorised as forest, when ecologically they are not (Figure 4).

The goal in this *State of the Forests* report is to measure forest and forest change in an ecologically meaningful way that makes sense in the PNG context. Developing such an understanding of what is happening in PNG's forests requires that savannah/woodland, garden and woody scrub growing on abandoned gardens, and uncleared forest, are mapped as separate classes. To this end, unless otherwise specified, 'forest' is defined as 'closed canopy rainforest', and does not include woody scrub and gardens, nor does it include timber plantations, which are mapped as separate classes. This definition allows any expansion of garden areas to be accurately measured. In this regard only the clearance of rainforest is mapped as deforestation, while the clearance of scrub that has been replaced with gardens is not included within 'deforestation' estimates. Within this report "forest degradation" is defined as the process of conversion of primary or climax forest into secondary forest through commercial logging or low intensity burning. Degraded, "secondary" forest results when significant damage has been caused to the forest's structure and ecology without the elimination of canopy cover. Degradation through commercial logging includes felling trees for timber and associated uses, associate damage to adjacent forest, vehicle access tracks to extract timber, haulage roads, wharves, areas cleared for log storage and other infrastructure.

Figure 1. Closed canopy rainforest in PNG in the lower Purari catchment of Gulf Province. This image shows 'forest' according to the State of the Forests report definition.

Figure 2. Lowland forest with shifting cultivation gardens, between Gasmata and Kimbe, West New Britain Province. Defining forest as an area 0.5 ha and over, greater than 10% canopy cover with > 5m tall trees, most of these garden areas would be mapped as 'forest', and garden expansion would not be recorded as deforestation. *Photo by Ed de Vogel.*

Figure 3. This landscape in East New Britain is a mosaic of garden, newly cleared in reddish brown, established in light green, as well as woody scrub, intermingled with patches of closed canopy rainforest. Using a definition of 'forest' as an area 0.5 ha and over in size with more than 10% canopy cover and trees capable of growing taller than 5 m, most of this area would be classified as 'forest', despite being mostly gardens and woody scrub.

Figure 4. Savannah woodland featuring scattered Eucalyptus papuana trees near Port Moresby. Defining forest as an area 0.5 ha and over, greater than 10% canopy cover with > 5m tall trees, this area of savannah woodland would be indistinguishable from closed canopy rainforest in a vegetation classification.

1.2 Vegetation extent in 2014

The 2014 State of the Forests study found that PNG had a land area of 461,739 square kilometres[2], of which 71% was covered by some form of forested landscape, including rainforest, mangrove, swamp forest and dry evergreen forest (Table 1 & Figure 5). Rainforest is the dominant vegetation in PNG, covering 60% of the country. By region, the largest expanse of rainforest covers the mainland coastal provinces (72%), with 15% covering the highland provinces, and 14% covering the island provinces (Table 1). Vegetation maps of each of PNG's provinces are provided in Chapter 9.

Table 1. Area of vegetation types by Province and region in 2014.

Province	Land area (km^2)	Rainforest (including secondary) (km^2)	Secondary rainforest (km^2)	Dry evergreen forest (km^2)	Swamp forest (km^2)	Mangrove (km^2)	Herbaceous swamp (km^2)	Scrub (km^2)	Grassland/ Woodland/ Cleared/ other non-forest (km^2)	Water (km^2)
Western	98,115	45,167	7,006	7,507	10,860	1,175	9,462	6,931	22,338	1,744
Gulf	34,550	23,311	4,846	0	5,013	2,605	350	1,065	1,674	521
Central	29,802	19,541	2,209	0	639	586	445	3,209	5,176	206
Milne Bay	14,196	9,125	1,046	0	124	446	2	2,078	2,374	48
Oro	22,608	15,369	946	0	1,939	161	274	1,848	2,825	187
Morobe	33,762	20,783	1,140	0	543	36	57	4,967	7,046	329
Madang	28,970	19,573	1,193	0	921	8	53	4,848	3,167	402
East Sepik	43,671	20,196	974	0	10,554	197	647	3,991	6,617	1,469
West Sepik	35,908	26,955	3,796	0	2,044	8	5	4,406	2,018	472
Mainland coastal region	**341,581**	**200,021**	**23,156**	**7,507**	**32,637**	**5,221**	**11,294**	**33,342**	**53,234**	**5,377**
Southern Highlands and Hela	25,598	18,574	74	0	179	0	0	2,904	3,740	201
Enga	11,730	7,989	0	0	2	0	0	1,240	2,461	37
Western Highlands and Jiwaka	9,123	4,941	0	0	0	0	0	1,435	2,711	36
Chimbu	6,134	3,596	0	0	1	0	0	1,109	1,396	32
Eastern Highlands	11,147	5,687	70	0	0	0	0	1,348	4,062	49
Highlands region	**63,731**	**40,787**	**144**	**0**	**183**	**0**	**0**	**8,037**	**14,371**	**356**
Mainland total	**405,312**	**240,809**	**23,301**	**7,507**	**32,820**	**5,221**	**11,294**	**41,379**	**67,605**	**5,733**
Manus	1,913	1,213	303	0	178	74	0	358	82	8
New Ireland	9,581	6,363	2,979	0	123	188	2	2,216	648	42
East New Britain	15,280	11,126	3,108	0	35	28	2	1,477	2,542	71
West New Britain	20,296	14,661	7,212	0	337	144	47	2,199	2,764	117
Bougainville	9,357	4,597	0	0	375	80	0	3,590	616	103
Islands region	**56,427**	**37,961**	**13,603**	**0**	**1,047**	**513**	**51**	**9,842**	**6,654**	**341**
TOTAL PNG	**461,739**	**278,767**	**36,902**	**7,507**	**33,866**	**5,734**	**11,346**	**51,223**	**68,164**	**6,074**

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[2] For a discussion of how area was calculated see Annex 1

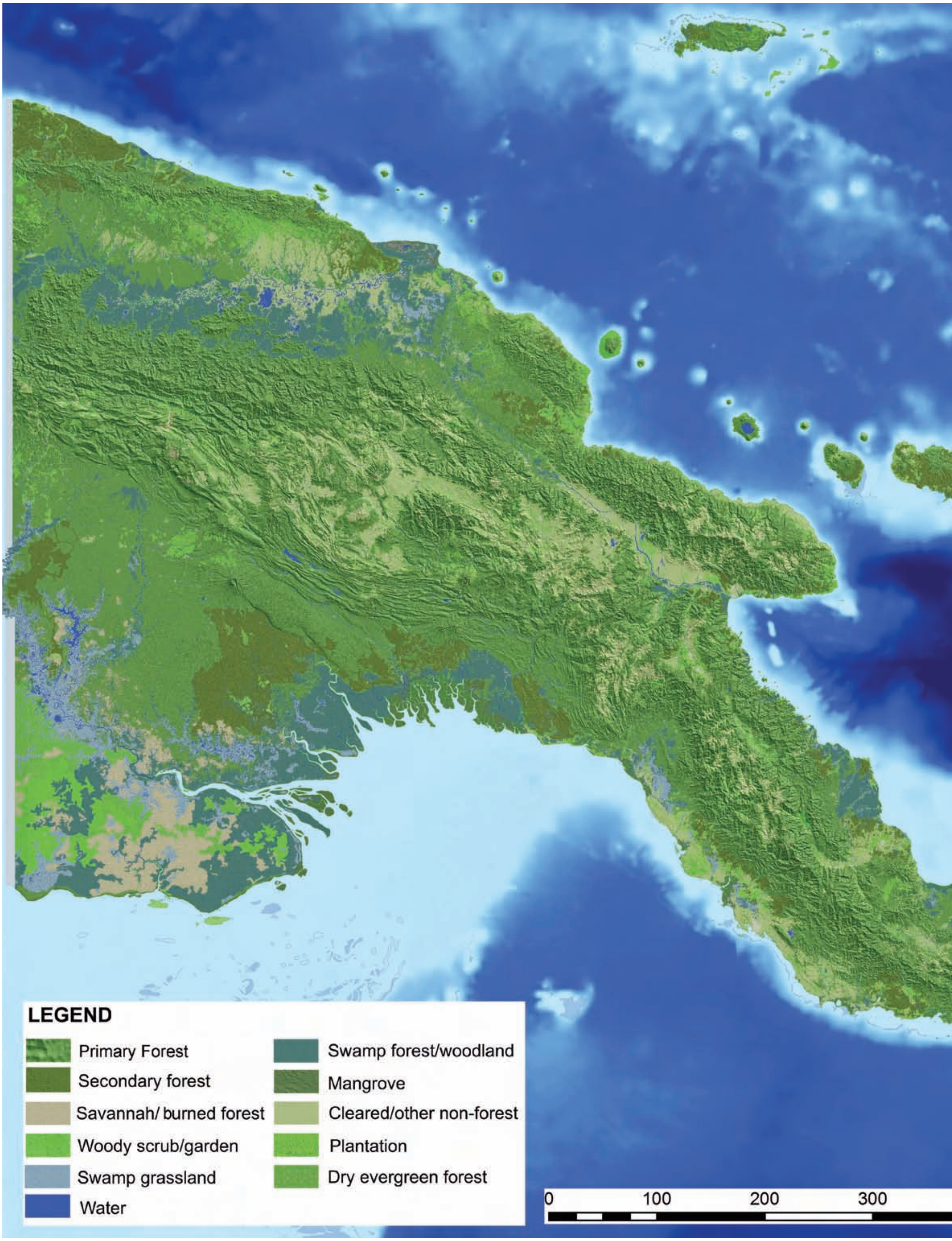

Figure 5. Vegetation in Papua New Guinea 2014.


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1.3 Forest change between 2002 & 2014

There have been substantial changes in PNG's forest estate between 2002 and 2014. During this period, a total of 3,752 km^2 of rainforest was cleared and 7,705 km^2 of previously unlogged forest was logged. Overall, 4.1% of the 2002 rainforest area was either cleared or logged by 2014 (Table 2). Of the total area of logged forests in PNG (36,902 km^2), 21% was logged for the first time during the 12 years between 2002 and 2014. The remaining 79% were first logged during the 30 years between 1972 and 2002. Much of this latter area has been re-logged, often multiple times, since then (see section 1.6).

There were substantial regional differences in deforestation and logging across PNG. As was the case between 1972 and 2002, the largest change in the study period occurred in the Islands region. There, logging was the major source of this change, with 7% of rainforest in Manus having been logged since 2002, and 5.9% of New Ireland (Figure 6). Major changes have also occurred in the forests of Gulf and West Sepik provinces (Figure 6). Over the three decades to 2002, 13% and 8% of forests in Gulf and West Sepik were logged respectively, however over the twelve years since 2002, an additional 6% of forests in Gulf, and an additional 5% in West Sepik were logged - a large increase in the quantum of change.

Table 2. Change in PNG's rainforest area (km^2) 2002-2014.

Province	Rainforest area 2014			Rainforest change 2002-2014				Total change (%)
	Total (km^2)	Unlogged (km^2)	Logged (km^2)	Deforested (km2)	Logged (km^2)	Deforested (%)	Logged (%)	
Western	45,167	38,161	7,006	583	1,476	1.3	3.2	4.5
Gulf	23,311	18,465	4,846	360	1,474	1.5	6.2	7.7
Central	19,541	17,332	2,209	89	409	0.5	2.1	2.5
Milne Bay	9,125	8,079	1,046	135	40	1.5	0.4	1.9
Oro	15,369	14,423	946	226	45	1.4	0.3	1.7
Morobe	20,783	19,644	1,140	182	38	0.9	0.2	1.1
Madang	19,573	18,380	1,193	376	455	1.9	2.3	4.2
East Sepik	20,196	19,223	974	273	532	1.3	2.6	3.9
West Sepik	26,955	23,159	3,796	329	1,394	1.2	5.1	6.3
Mainland coastal region	**200,021**	**176,865**	**23,156**	**2,553**	**5,864**	**1.3**	**2.9**	**4.2**
Southern Highlands and Helaa	18,574	18,501	74	196	1	1.0	0.0	1.0
Enga	7,989	7,989	0	90	0	1.1	0.0	1.1
Western Highlands and Jiwaka	4,941	4,941	0	39	0	0.8	0.0	0.8
Chimbu	3,596	3,596	0	42	0	1.1	0.0	1.1
Eastern Highlands	5,687	5,617	70	39	0	0.7	0.0	0.7
Highlands region	**40,787**	**40,643**	**144**	**406**	**0**	**1.0**	**0.0**	**1.0**
Mainland total	**240,809**	**217,508**	**23,301**	**2,960**	**5,864**	**1.2**	**2.4**	**3.6**
Manus	1,213	911	303	27	86	2.1	7.0	9.1
New Ireland	6,363	3,384	2,979	105	385	1.6	5.9	7.6
East New Britain	11,126	8,018	3,108	259	577	2.3	5.1	7.3
West New Britain	14,661	7,449	7,212	330	793	2.2	5.3	7.5
Bougainville	4,597	4,597	0	70	0	1.5	0.0	1.5
Islands region	**37,961**	**24,359**	**13,603**	**790**	**1,842**	**2.0**	**4.8**	**6.8**
TOTAL PNG	**278,767**	**241,866**	**36,902**	**3,752**	**7,705**	**1.3**	**2.7**	**4.1**

The study found that there were substantial regional differences in the areas deforested in the period 2002-2014, with much of these forest losses concentrated in the island provinces. East (2.3%) and West New Britain (2.2%) provinces had the largest proportion of their forests cleared. The highlands provinces overall underwent the least change, with only 1% of 2002 forest area cleared by 2014. The absence of large scale industrial logging from the highlands explains the comparatively low rate of forest change compared to the lowlands and islands where logging is concentrated.

Although it is still the case that the island provinces are where industrial logging has been most heavily concentrated, it is clear that there has been a substantial acceleration of industrial logging in the lowland forests of the mainland. By far the biggest area of recent logging occurred in the lowland forests of West Sepik, Gulf and Western provinces (Figure 7, Figure 8). This shift of the logging industry from the islands to these areas is probably due to the reduction in areas of unlogged easily accessible areas of forest in the islands.

At the national level, 4.1% of forests were either cleared or logged over the 12 year period. This suggests a reduction in the rate of change that was found in the period between 1972 and 2002 (Shearman *et al.* 2008). Much of the change in this earlier period occurred in the latter years of those decades, at an estimated annual rate of deforestation and forest degradation of 1.4% between 2001 and 2002 (Shearman *et al.* 2008). In contrast, the estimated annual rate of deforestation and degradation for 2013-2014 was 0.49% (see full methods in Annex 1).

While there has been an overall deceleration in both the areas that have been cleared and logged, most of this reduction has been in deforestation. Logging of previously unlogged forests has continued at a greater rate than has deforestation. This means that forestry was responsible for a greater proportion of overall change since 2002. Between 1972 and 2002, the major drivers of forest change were logging, accounting for 48% of total change, subsistence agriculture (and landslides) accounting for 46%, and fire accounting for 4% of total change (Shearman *et al.*, 2008). In contrast, between 2002 and 2014, 81% of total change (deforestation and degradation) and 41% of total deforestation were caused by logging and occurred inside active logging operations (see Annex 1 for full methods).

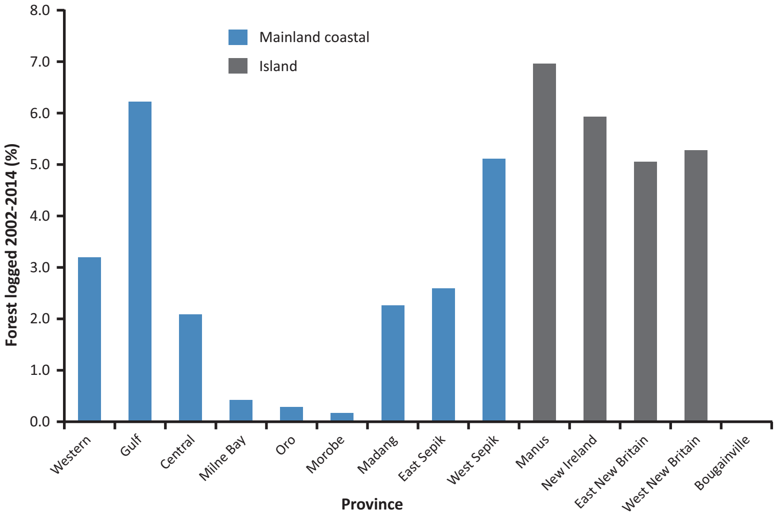

Figure 6. Percentage of the 2002 forest area logged between 2002 and 2014.

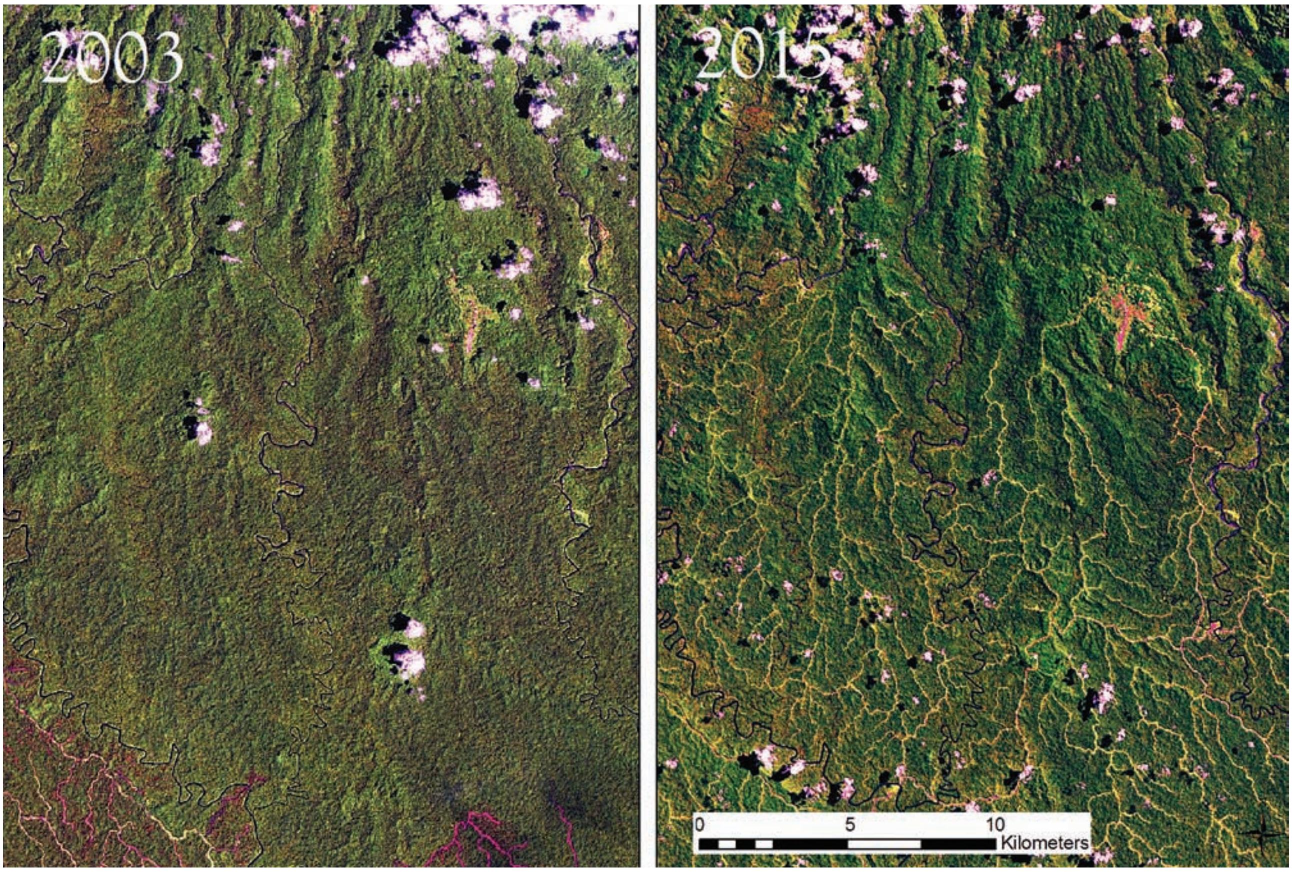

Figure 7. Expansion of logging in the lowland forests of Western province in the Wawoi Guavi logging concession. Intact forest appears in dark green, new logging and new logging roads can be seen in pink in the bottom of the 2003 image. In 2015 logging roads built since 2003 appear in yellow/light green across the whole area.

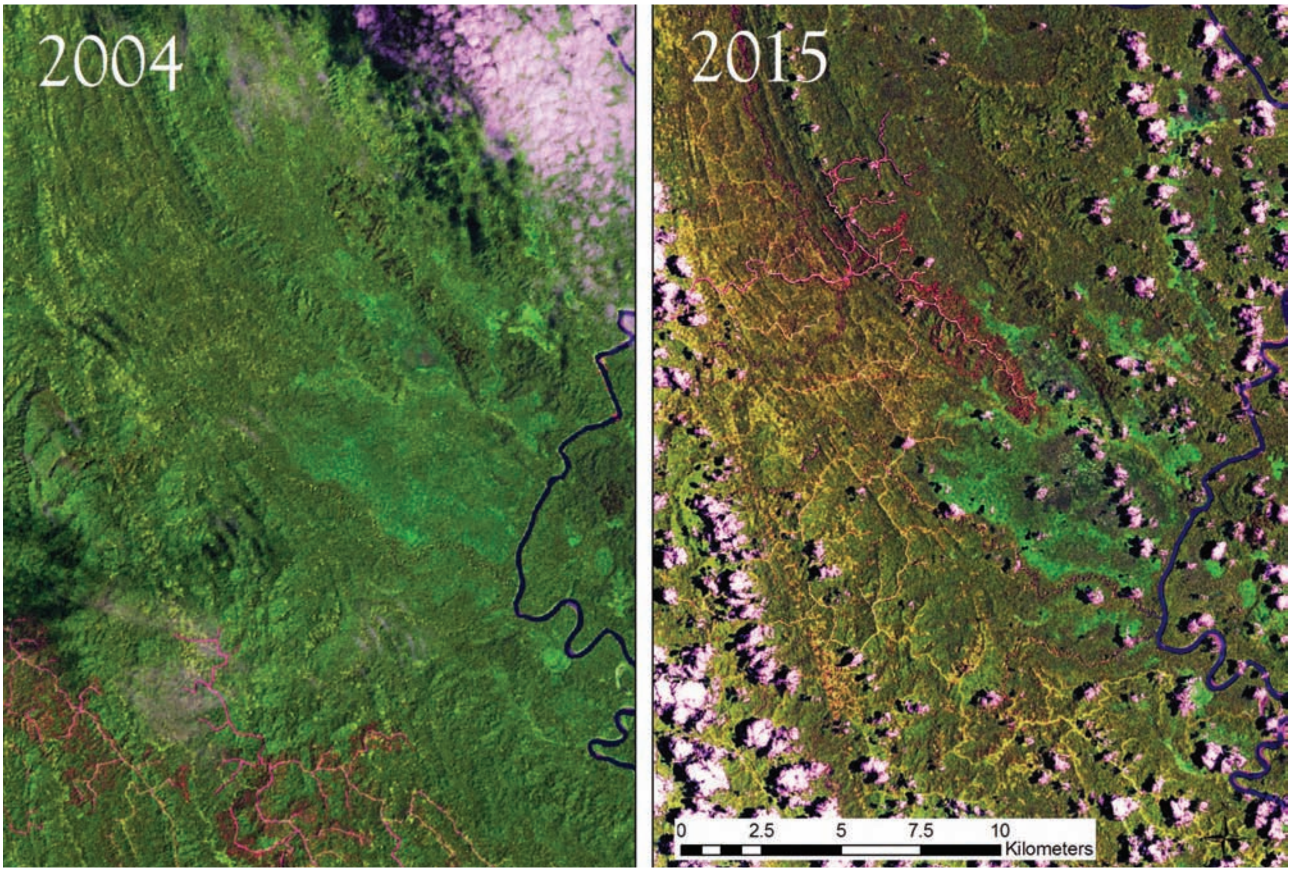

Figure 8. Expansion of logging in the lowland forests of Gulf province, Vailala Block 3. Intact forest appears in dark green while new logging and new logging roads can be seen in pink in the bottom of the 2004 image. In 2015, older logging roads built since 2004 appear in yellow/light green across the whole area. New logging roads and harvesting appear in pink at the top of the image.

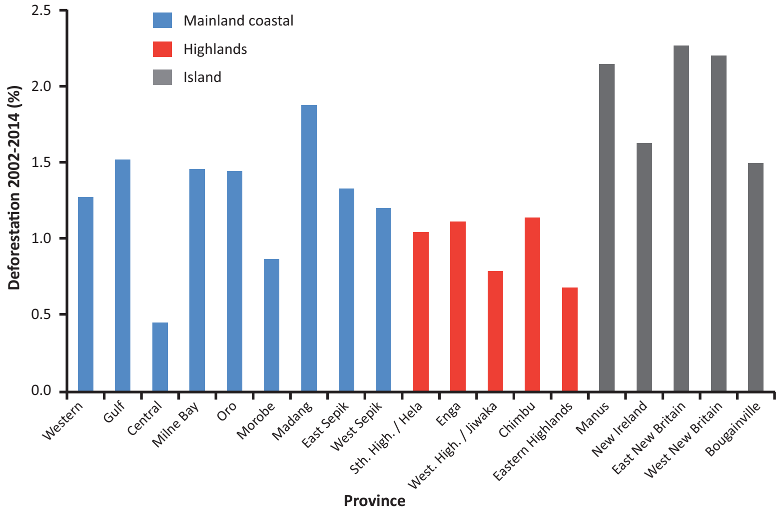

Figure 9. The percentage of the 2002 forest area cleared between 2002 and 2014.

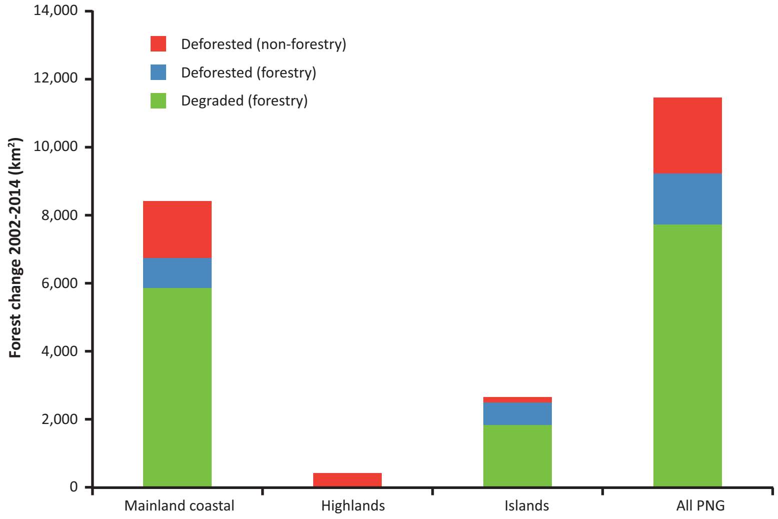

Figure 10. Regional change between 2002-2014, forest degraded by logging (degraded), deforested by forestry activity and deforested by non-forestry processes.

Changes in the logging industry and fire regimes in PNG, as well as changes to PNG's economy partially explain why there was a reduction in the rate of forest change between 2002 and 2014, in comparison with the preceding three decades. In 1997/1998 there was a major El Niño event which caused lower than average rainfall and higher than average temperatures in PNG and across the South East Asian and Australian region. As a result of these dry conditions, large fires occurred in the forests of the region, and in PNG caused the die-back or loss of several hundred thousand hectares of rainforest. Since that time there has been no El Niño event to rival that of 1997/1998 which partially explains the reduction in deforestation. However, this may change in future, as 2015 is witnessing another El Niño event potentially on a magnitude similar to that of 1997/1998.

Over the period 2002-2014 there was also a deceleration in logging-related deforestation. This was likely the result of recent timber production relying to a greater degree on repeat logging of already logged forests, rather than new entry into unlogged forest. One of the drivers of deforestation in active logging areas is road-building, however this only need occur once in each logging coupe. When forests have been harvested once, subsequent harvests tend to use the same logging roads. Hence PNG experienced a peak in logging related deforestation prior to 2002, when the majority of forests within logging concessions were logged. Since 2002, this road-building has slowed. However, with the onset of another major El Niño in 2015, those forests that have been repeatedly harvested are primed for burning, and the post-2015 period may see another forestry-related deforestation peak in PNG.

A third reason for the slow down in deforestation is potentially due to a decline in clearing intact forest for subsistence agriculture. It is possible that the boom in mineral exports from PNG between 2002 and 2014 led to a transition of a significant portion of the population from subsistence agriculture into the cash economy. This would mean more people are purchasing imported or industrially produced food with less need to expand food gardens into forest. Alternatively, or perhaps additionally, it might also be the case that land scarcity, especially in the highlands, has led to existing cultivated land being more intensively used.

1.4 Forest Change in Special Agriculture and Business Leases

Prior to 2002, large forest clearances for industrial agriculture were relatively minor and accounted for only 1.2% of total forest change in the preceding 30 years. However, since 2002 the PNG government has embarked on a plan to dramatically expand the industrial agriculture sector by issuing leases allowing the clear-felling of forests for agricultural development. These leases are called "Special Agriculture and Business Leases" (SABLs). Although the stated intent of SABLs is for agricultural development, it has been argued that some of these leases are being used by the logging sector as de facto logging concessions in order to bypass PNG's forestry laws (Nelson *et al.*, 2014). The current state of forests within SABLs, and changes that occurred 2002-2014 were assessed with a view to exploring this issue.

A PNG government commission of inquiry into SABLs investigated 75 of these leases covering ≈52,000 km^2 (Numapo 2013). This study examined forest change within the 52 largest of these that in total covered 90% of the total SABL area (Figure 11). Within these leases 76% was rainforest, most of which (89%) had never been logged. Between 2002 and 2014, 2,047 km^2 of rainforest were logged or cleared inside SABLs. Of these 2047 km^2, 77% occurred within active logging operations and were not followed by agricultural planting within the study period (Figure 12).

Only 7% of the total forest area that was cleared or logged actually resulted in some form of industrial agricultural plantation and only 20% of those areas that were deforested were replaced with industrial plantations within the study period (Figure 12). While this finding is similar for the vast majority of SABLs, there was substantial variation in what occurred within individual leases (full change statistics for individual SABLs are presented in Annex 2). There were four SABLs where more than 20% of the total forest area logged or cleared and were subsequently planted with oil palm. Two of these were in West Sepik province (Figure 13), and two were in East New Britain (Figure 14). Both of these provinces are focal areas for expansion of the oil palm industry. Of particular note is the new clear-felling in West Sepik which will allow the first substantial oil palm operation in the north west of the country.

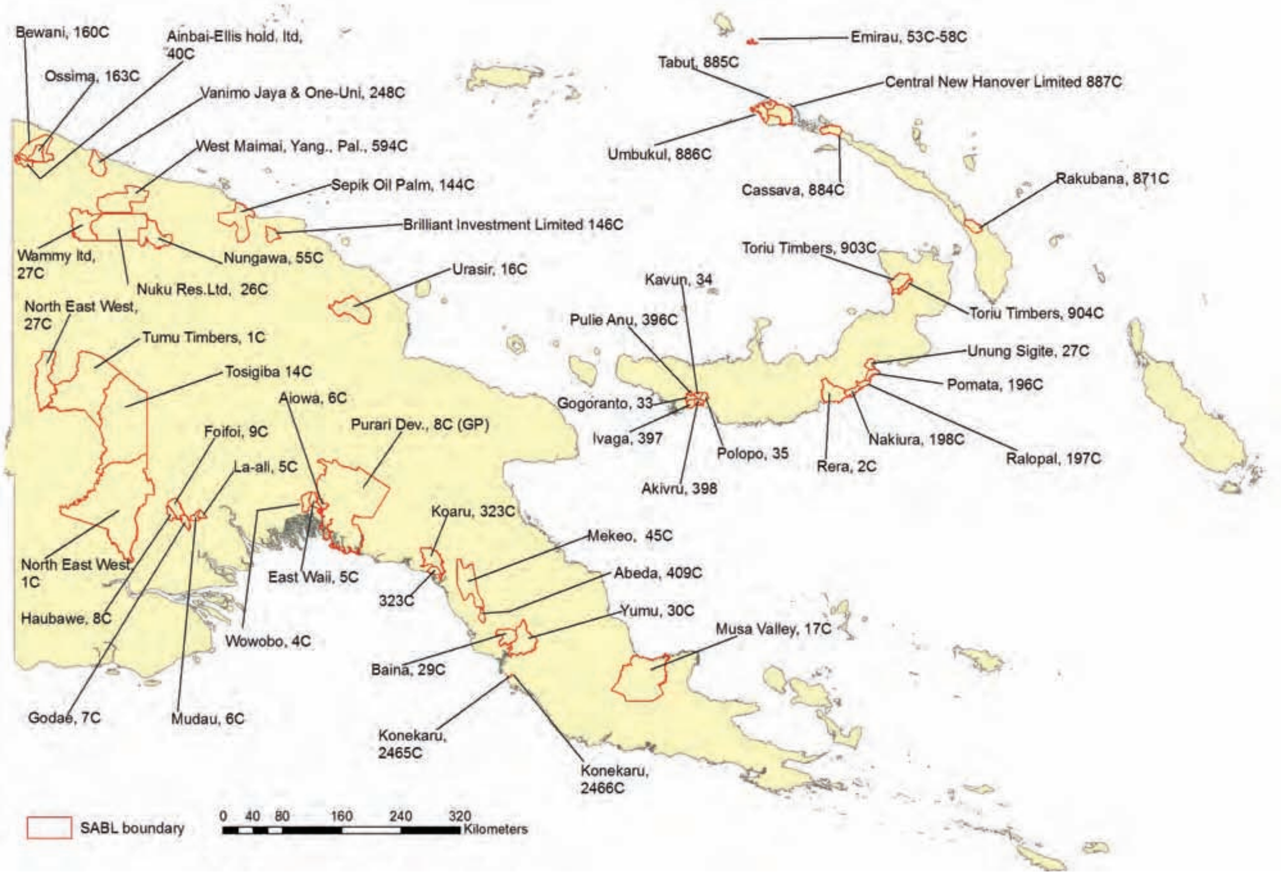

Figure 11. Abbreviated name of each SABL grantee and portion number.

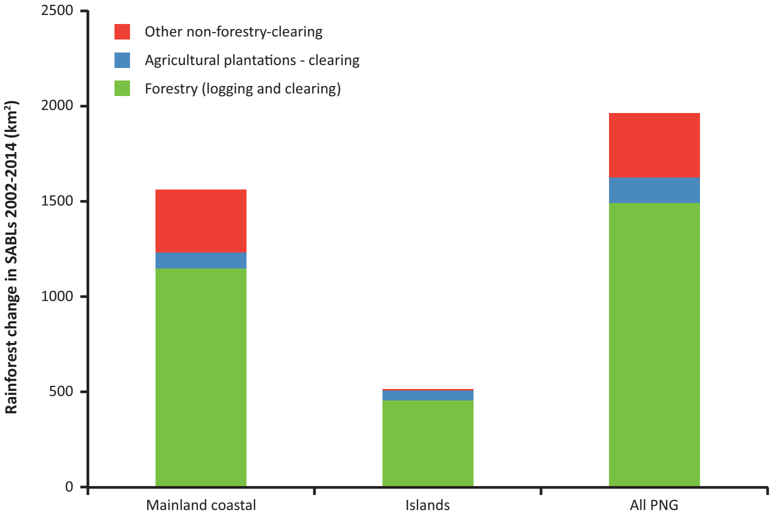

Figure 12. Rainforest change 2002-2014 inside SABLs. The area of logging (selective logging) and clearing (roads, log ponds, logging camps etc) associated with forestry is shown in green. The area cleared and replaced with agricultural plantations is shown in blue, and all other clearing not associated with either industrial agriculture or industrial logging is shown in red. This is principally clearing for subsistence agriculture and unrelated to industrial plantations.

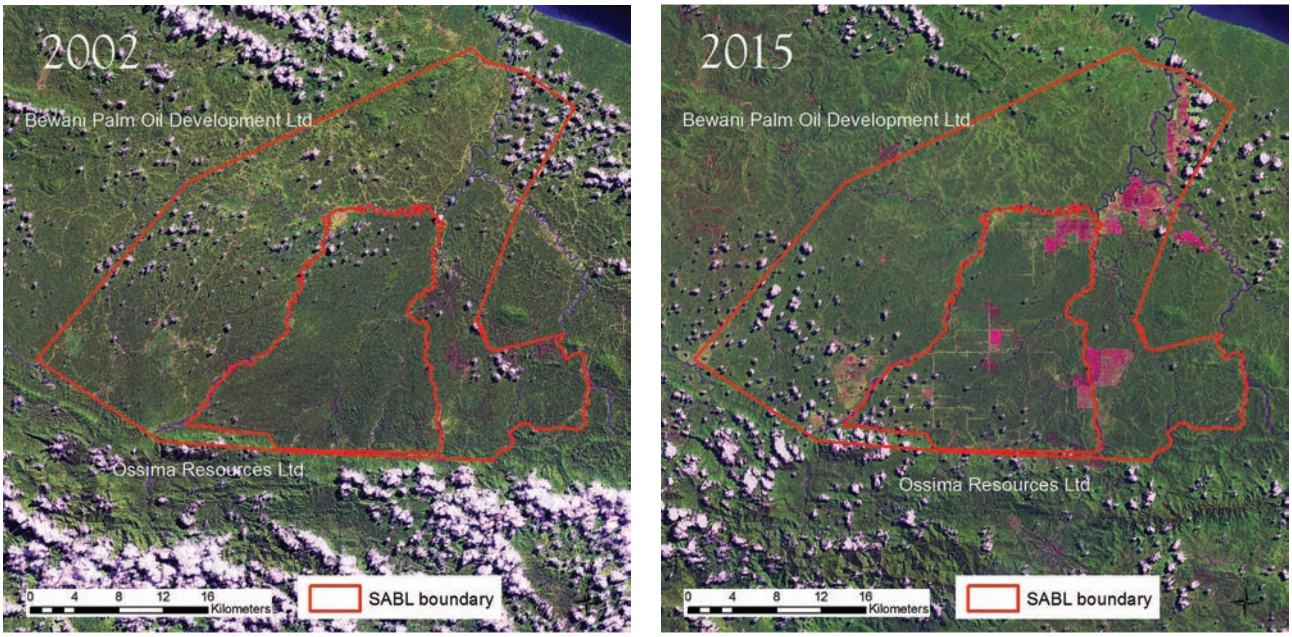

Figure 13. Clearing for oil palm inside the Bewani Palm Oil Development Ltd and Ossima Resources Ltd SABLs in West Sepik province, near Vanimo. The 2002 image was recorded on 21 May 2002. Forest appears in dark green where no clear felling for oil palm has occurred. The 2015 image was recorded on 21 August 2015. Extensive clear-fells and oil palm plantations appear in pink and light green.

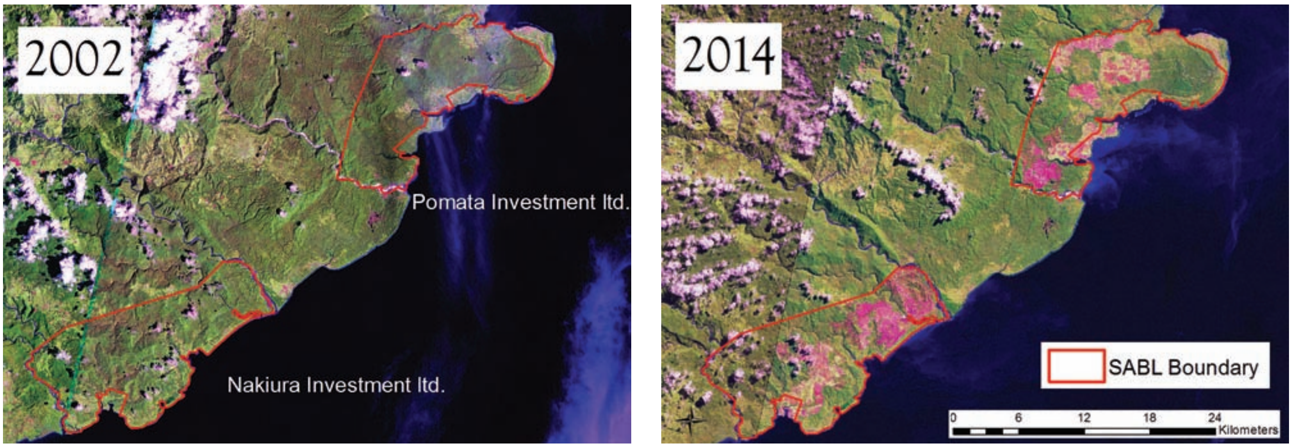

Figure 14. Clearing for oil palm inside the Pomata Investment Ltd and Nakiura Investment Ltd SABLs in East New Britain province. The 2002 image was recorded on 11 January 2002. Forest appears in dark green where no clear felling for oil palm has occurred. The 2015 image was recorded on 7 July 2014. Extensive large clear-fells and oil palm plantations appear in pink and light green.

While SABLs are presently being used by the industrial logging sector for the extraction of timber, the substantial clearing of forest for oil palm in some SABLs indicates that this may change in future. It should also be noted that three entire logging concessions, Kamula Doso Block1, Block 2 and Block 3 have been placed inside three SABLs. The allocation by the Papua New Guinea Forest Authority (PNGFA) of the three Kamula Doso blocks for logging was found to be unlawful after a Non Government Organisation (NGO) on behalf of local land owners challenged its allocation in the PNG courts (see section 1.6.3). As a result of the court challenge, logging of Kamula Doso never went ahead, and the whole region remains unlogged, but is nevertheless inside both a proposed logging concession, and an SABL.

1.5 Forest Change in Commercially Accessible forest

The major reason why the logging industry is concentrated in the mainland lowlands and islands is the greater accessibility of these forests. In 2014, it is estimated that there were 115,305 km^2 of forests accessible to the industrial logging sector, of which 77% was located in the mainland coastal provinces, and 19% in the islands (Table 3). Much greater change occurred in commercially accessible forests compared to the overall forest areas. Since 2002, 7.3% of accessible forests were cleared or logged - much greater than the 4.1% that was cleared or logged overall.

Table 3. Change in PNG's commercially accessible rainforest area (km^2) 2002-2014.

	Accessible rainforest area 2014			Accessible rainforest change 2002-2014				
Province	**Total (km^2)**	**Unlogged (km^2)**	**Logged (km^2)**	**Deforested (km^2)**	**Logged (km^2)**	**Deforested (%)**	**Logged (%)**	**Total change (%)**
Western	36,104	29,098	7,006	44	1,476	0.12	4.08	4.21
Gulf	13,463	8,617	4,846	66	1,474	0.49	10.90	11.38
Central	4,959	2,750	2,209	19	409	0.39	8.22	8.61
Milne Bay	2,628	1,582	1,046	14	40	0.51	1.52	2.04
Oro	6,124	5,178	946	57	45	0.92	0.73	1.66
Morobe	1,998	859	1,140	27	38	1.36	1.89	3.25
Madang	6,369	5,176	1,193	25	455	0.39	7.12	7.50
East Sepik	4,427	3,453	974	34	532	0.76	11.93	12.68
West Sepik	12,684	8,888	3,796	72	1,394	0.57	10.93	11.49
Mainland coastal region	**88,757**	**65,601**	**23,156**	**359**	**5,864**	**0.40**	**6.58**	**6.98**
Southern Highlands and Hela	3,127	3,053	74	1	1	0.03	0.02	0.05
Enga	140	140	0	0	0	0.00	0.00	0.00
Western Highlands and Jiwaka	666	666	0	0	0	0.00	0.00	0.00
Chimbu	506	506	0	0	0	0.00	0.00	0.00
Eastern Highlands	71	0	70	1	0	0.82	0.00	0.82
Highlands region	**4,510**	**4,366**	**144**	**2**	**0**	**0.04**	**0.00**	**0.04**
Mainland total	**93,267**	**69,967**	**23,301**	**360**	**5,864**	**0.38**	**6.26**	**6.65**
Manus	780	478	303	5	86	0.67	11.01	11.67
New Ireland	3,741	763	2,979	35	385	0.91	10.19	11.10
East New Britain	4,876	1,768	3,108	111	577	2.23	11.57	13.79
West New Britain	10,958	3,746	7,212	219	793	1.96	7.09	9.05
Bougainville	1,682	1,682	0	0	0	0.00	0.00	0.00
Islands region	**22,038**	**8,436**	**13,601**	**370**	**1,841**	**1.65**	**8.22**	**9.87**
TOTAL PNG	**115,305**	**78,403**	**36,902**	**730**	**7,705**	**0.63**	**6.64**	**7.27**

Of the remaining accessible forests, 32% were logged by 2014 - up from 25% in 2002. However there was large regional variation, with the island provinces having the majority of their accessible forests already logged at least once. By 2014, 80% of the accessible forests in New Ireland had been logged - up from 69% in 2002. Similarly, 66% of accessible forests in West New Britain and 64% in East New Britain have already been logged at least once, up from 57% and 51% respectively in 2002. Gulf, Western and West Sepik provinces between them contain 59% of all remaining commercially accessible unlogged forests.

1.6 The State of PNG's Logging Concessions

Industrial logging in PNG takes the form of selective logging, whereby only sufficiently large, commercially saleable species are harvested, and remaining trees are left standing. While only a selection of trees are harvested, this form of logging still causes substantial damage (Bryan *et al.*, 2010), with repeated logging cycles (typically 20-40 years) leading to further degradation over time (Putz *et al.*, 2008, Putz *et al.*, 2012). During selective logging, forest biomass is lost in the form of the harvested logs, wastage from felled trees, in the wood used to build logging infrastructure, through collateral damage to surrounding trees, and through clearance for roads and skid trails. Damage to soils, siltation of waterways (Figure 15, Figure 16), and substantial carbon emissions also result from logging (Putz *et al.*, 2008, Bryan *et al.*, 2010), and logged forests are more susceptible to burning, invasive species incursion and eventual deforestation (Holdsworth & Uhl, 1997, Nepstad *et al.*, 1999, Asner *et al.*, 2005, Asner *et al.*, 2006).

Figure 15. Damage caused by selective logging in northern PNG.

Figure 16. Soil erosion and water siltation from a logging operation in northern PNG.

Logging in PNG is primarily centred on harvesting unprocessed round logs from natural forest for export. There is very little local timber milling or processing (Forest Trends 2006a,b). Since 1972, there has been a large increase in the volume of timber exported from PNG (Figure 17) with log exports reaching an all-time high of 3.2 million m^3 in 2014. Of note are the big falls in production after the Asian financial crisis in 1997 and the global financial crisis in 2008. Log production in PNG has been closely linked with trends in global financial markets.

The PNG Forest Authority (PNGFA) oversees forestry in PNG under a system of logging concessions. The majority of logging concessions are leased and operated by foreign owned companies, primarily from Malaysia, and most logs (89% in 2013) are exported to China (Bun *et al.*, 2004, Bryan 2012, ITTO 2014). In 2014 there were 298 current and proposed concessions covering 14.9 million ha of rainforest. Between 1972 and 2014, logging occurred within 228 of these concessions. While the majority of this logging activity occurred within designated concession boundaries, some has occurred outside these concessions (Figure 18).

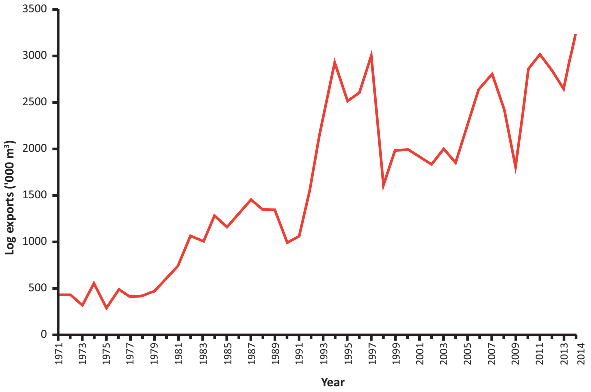

Figure 17. Export of round logs (in thousands of m^3) from Papua New Guinea 1971-2014. Log volumes derived from Bank of PNG annual reports.

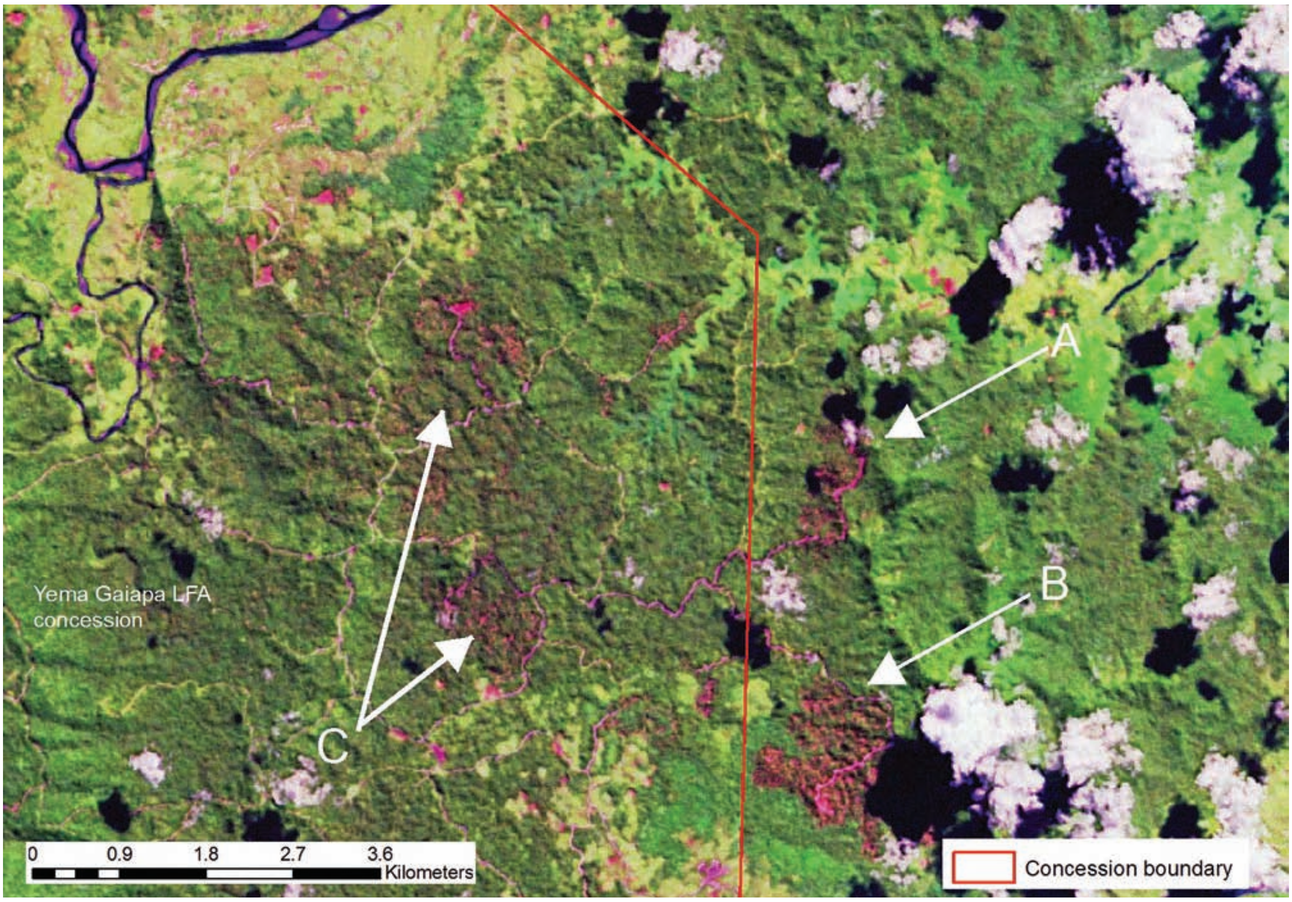

Figure 18. Logging outside the concession boundary at Yema Gaiapa logging concession, Oro province. This image is Landsat 8 infra-red enhanced recorded on 24/7/2015. New logging and clearing can be seen in pink, in areas A, B and C. Areas A and B are outside the concession boundary, area C is inside. Forest appears in dark green, swamp in light green, woody scrub/garden in yellow.

The huge increase in timber volumes in recent decades has resulted in many concessions being almost fully exhausted. By 2014, there were 72 concessions in which more than 80% of accessible forests had already been logged at least once, with 38% of these located in West New Britain province. The Vanimo Timber Rights Purchase (TRP) concessions in north of West Sepik province (Figure 19), and the Wawoi Guavi concessions in Western province stand out as concessions where almost all commercially accessible forests have already been logged at least once (Figure 19).

The PNG logging industry operates under the PNG Logging Code of Practice, a set of Reduced Impact Logging (RIL) principles. These include harvesting limited to commercial trees greater than 50 cm diameter at breast height, buffer zones along watercourses, 'setup' or coupe plans marking out the location of skid trails, and cutting of vines before logging begins. Local landowners have the option of maintaining up to 10% of a concession as protected areas, although this is rarely exercised. New Guinea forests have trees with smaller canopies and produce lower volumes of merchantable timber compared to other tropical nations; typically 10-20 m^3 ha^{-1} (Shearman *et al*., 2009, Bryan *et al*,. 2010, Bryan 2012, Wilkinson 2013).

In theory therefore, the older concessions which have completely or very nearly completely logged all accessible forests, should be ready to be re-allocated for a second harvest starting in those parts of the concession first logged 35 years ago. However, repeat harvests of forests within the 35 year period have been common across PNG (Katsigris *et al*., 2004, Bryan *et al*., 2010, Bryan 2012).

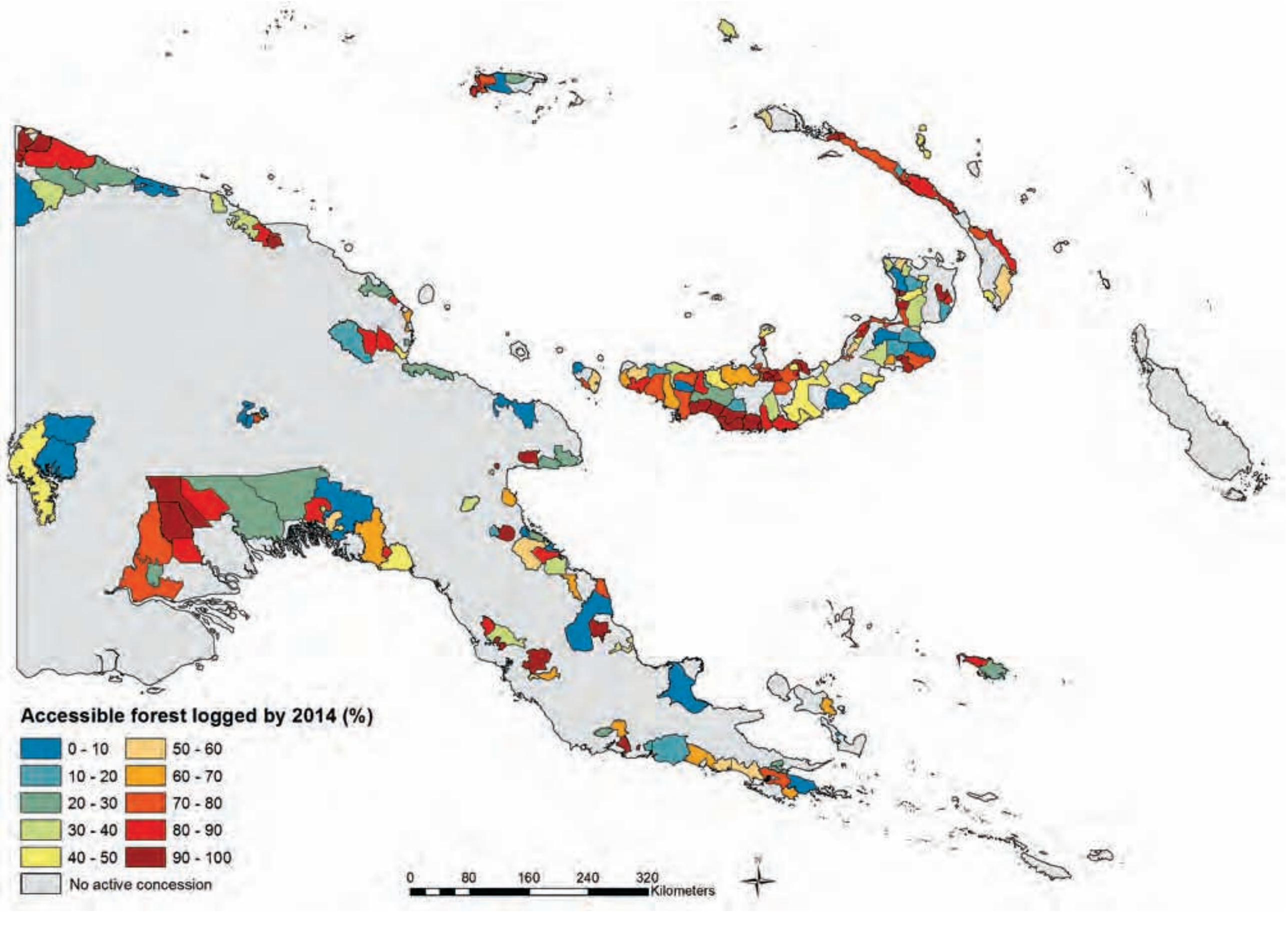

Figure 19. The percentage of commercially accessible forests already logged at least once by 2014 in active logging concessions. Only concessions where logging activity took place between 1972 and 2014 are shown.

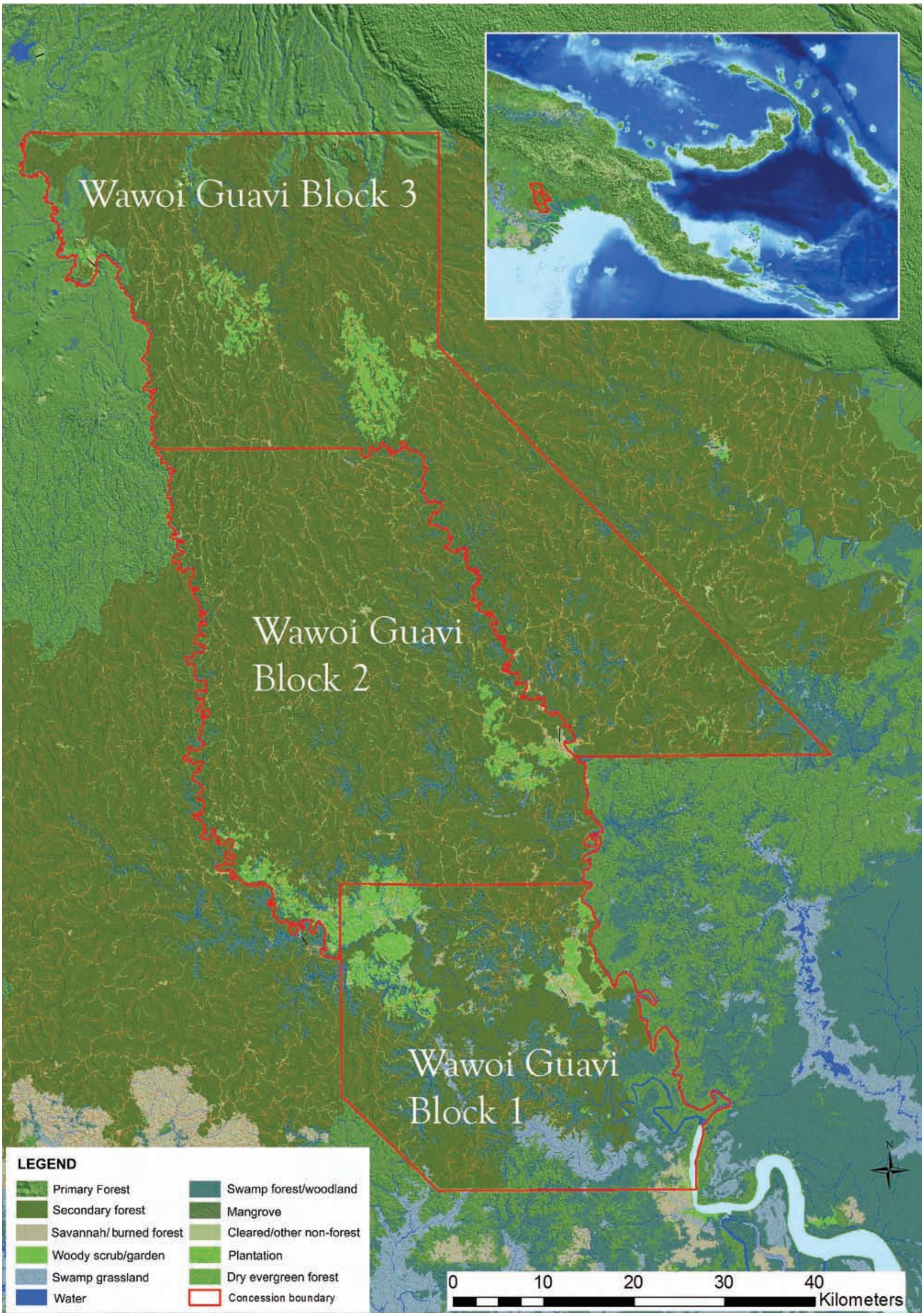

Figure 20. Vegetation in the Wawoi Guavi logging concessions in 2014.

1.6.1 Forestry management in logged forests: A case study of the Wawoi Guavi logging concession

The major problem of repeated re-entry logging is exemplified by examining what occurred in the Wawoi Guavi concessions. Three separate concessions (Wawoi Guavi Block 1, Wawoi Guavi Block 2, Wawoi Guavi Block 3) make up Wawoi Guavi (Figure 20), with Block 1 acquired as a concession in 1981, Block 2 in 1983, and Block 3 in 1989.

Using Landsat satellite imagery recorded at successive dates between 1983 and 2015, the progression of logging across the three concessions was documented[4]. Logging roads were first apparent in the satellite imagery at the border between Block 1 and 2 in 1983 - the extent of these logging roads in early 1984 is shown in Figure 21. By 1989, 13% of the Wawoi Guavi concessions were impacted by logging roads and harvesting. This zone more than doubled over the next 5 years - by 1994, 29% of the concessions had been logged. By 2005, logging roads impacted 84% of the concessions, and by 2015 almost the entire land area within the concession had been logged.

The change assessment undertaken in this study suggests that by 2002, 87% of the accessible forests in Block 1 and 100% of accessible forests in Block 2 had already been logged. Of the remaining unlogged accessible forests in Block 1, most are adjacent to swamps and are unlikely to be logged (Figure 20), therefore Block 1 was for practical purposes completely logged by 2002. In Block 3 by 2002, 63% of accessible forests had been logged; rising to 93% by 2014 (Figure 20).

Despite these blocks having been almost fully logged by 2002, timber production in these concessions did not stop. As logging began in 1983, according to the PNG Logging Code of Practice, repeat harvests are not due to begin until 2018, 35 years after the first forests were logged. However, re-entry logging occurred in many locations well within the 35 year cutting cycle (Figure 22, Figure 23). In some areas, re-entry harvesting within 15 years was detected. This is less than half the length of the 35 year cutting cycle.

Over the period between 2002 and 2012, 1.6 million m^3 of roundlogs were exported from Wawoi Guavi. Log volumes for 2013 and 2014 were not available, but conservatively assuming that volumes in those years were the average of the previous five years (2008-2012), then approximately 1.9 million m^3 were exported over the period 2002-2014. This study found that between 2002 and 2014, 53,602 ha of accessible forests were logged in Wawoi Guavi. If all the logs exported had come from first harvests of previously unlogged forests, it implies an average harvest intensity of 35 m^3 ha^{-1}, not accounting for any wastage between harvest and export. Yet first harvests in PNG (and especially in Western Province) typically produce only 10-20 m^3 ha^{-1} (Shearman *et al*, 2009, Bryan *et al.*, 2010, Bryan 2012, Wilkinson 2013). Assuming that actual harvest intensities in Wawoi Guavi were somewhere between 10 and 20 m^3 ha^{-1}, it suggests that 40-70% of timber produced in Wawoi Guavi 2002-2014 was derived from re-entry logging.

While almost all accessible forests inside Wawoi Guavi have already been logged at least once, timber production in these concessions has been maintained by repeat harvesting of already logged forests. Wawoi Guavi is not the only concession where re-entry logging has occurred. Repeat harvesting within 35 years is common in older logging concessions (Bryan 2012). Two examples are shown from West New Britain and West Sepik in Figure 24 and 25.

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[4] See Annex 1 for detailed methods.

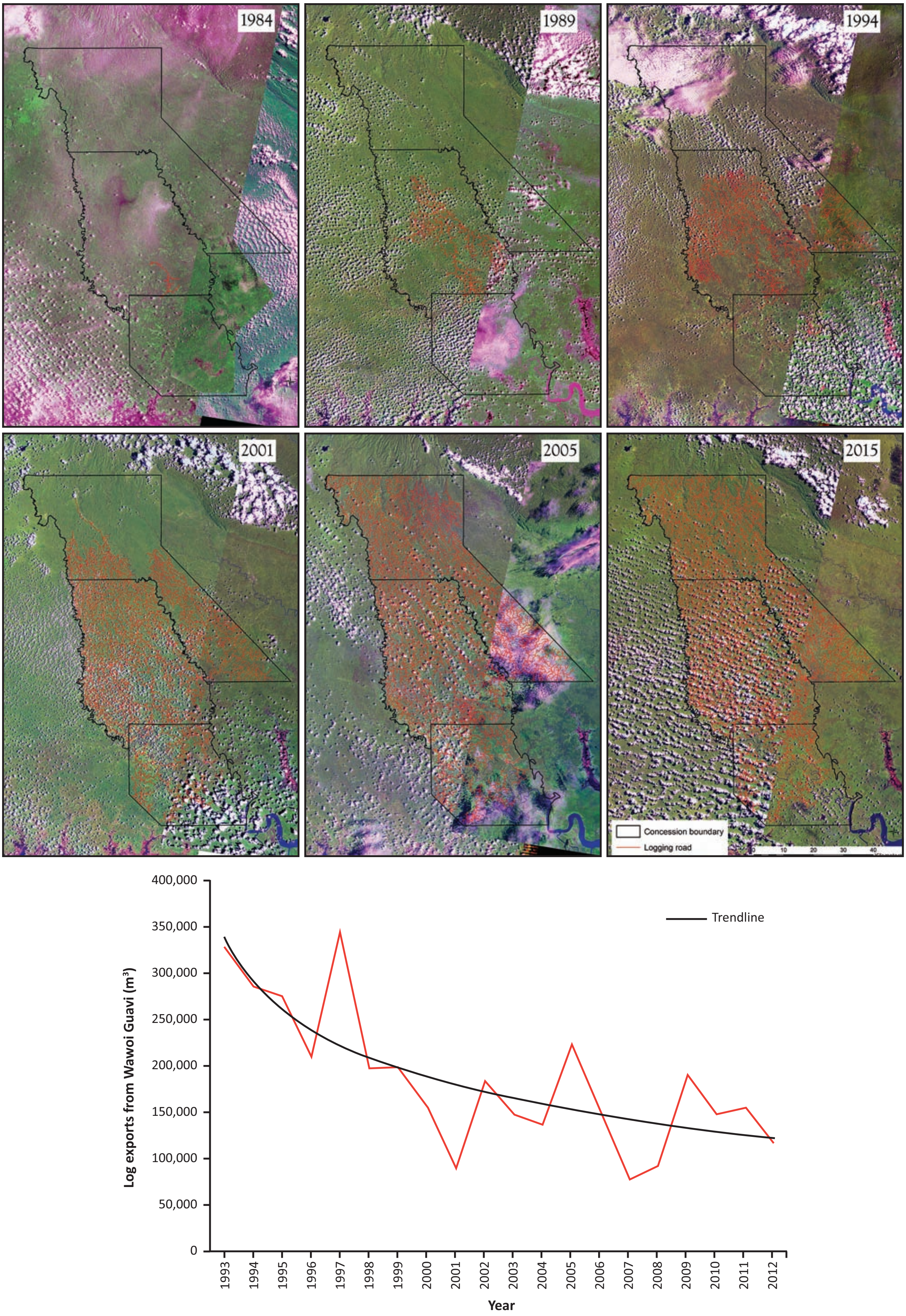

Figure 21. The expansion of logging activity in the Wawoi Guavi Blocks between 1984 and 2015. Log exports from the Wawoi Guavi concessions 1993-2012 are also shown, obtained from SGS reports.

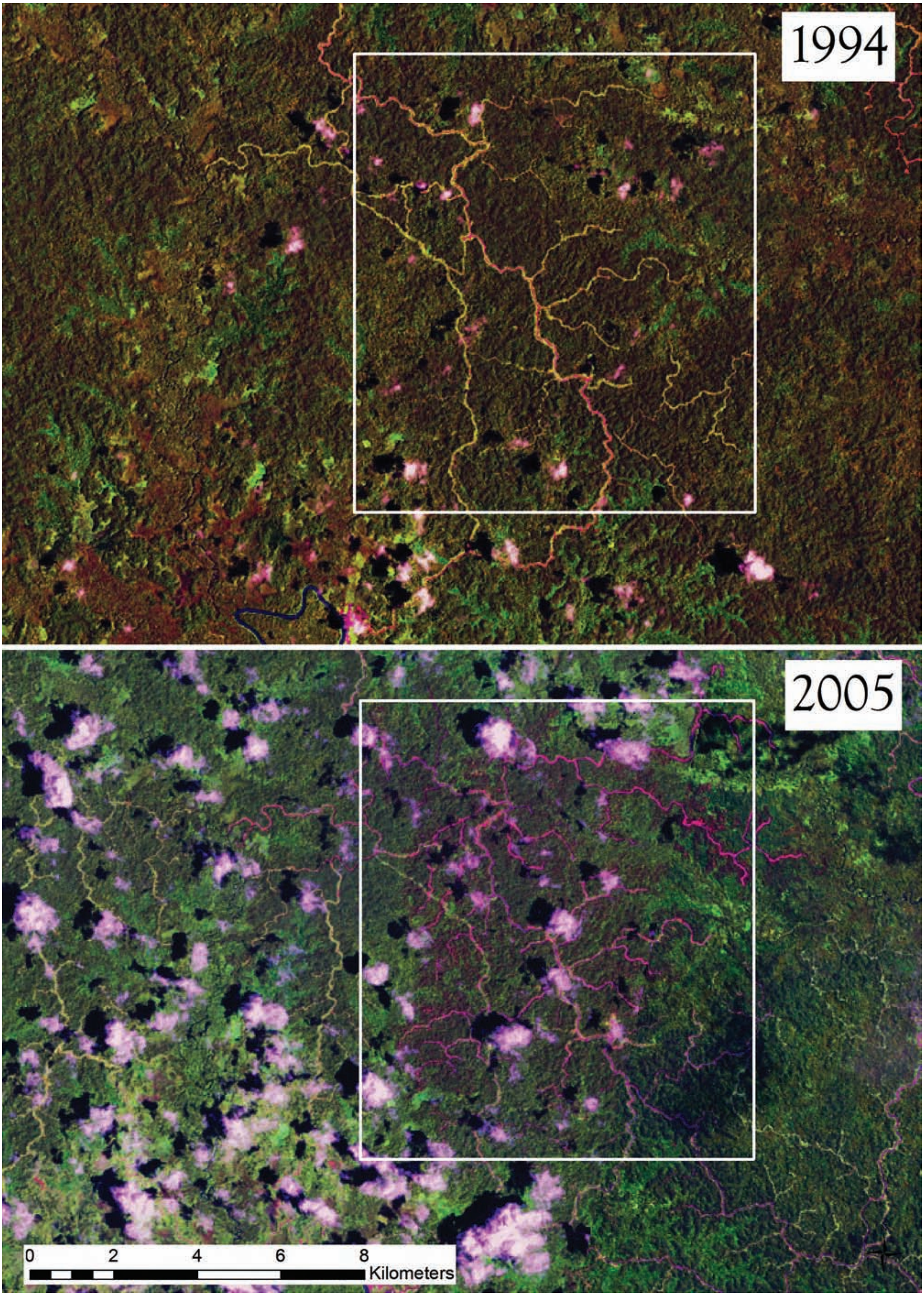

Figure 22. Repeat harvesting of the same forest within 35 years in Block 2 and Block 3 Wawoi Guavi. The 2005 image was recorded on January 2005. Recent harvesting appears in pink/purple. The 1994 image was recorded on 8 February 1994 and shows the same area had already been logged.

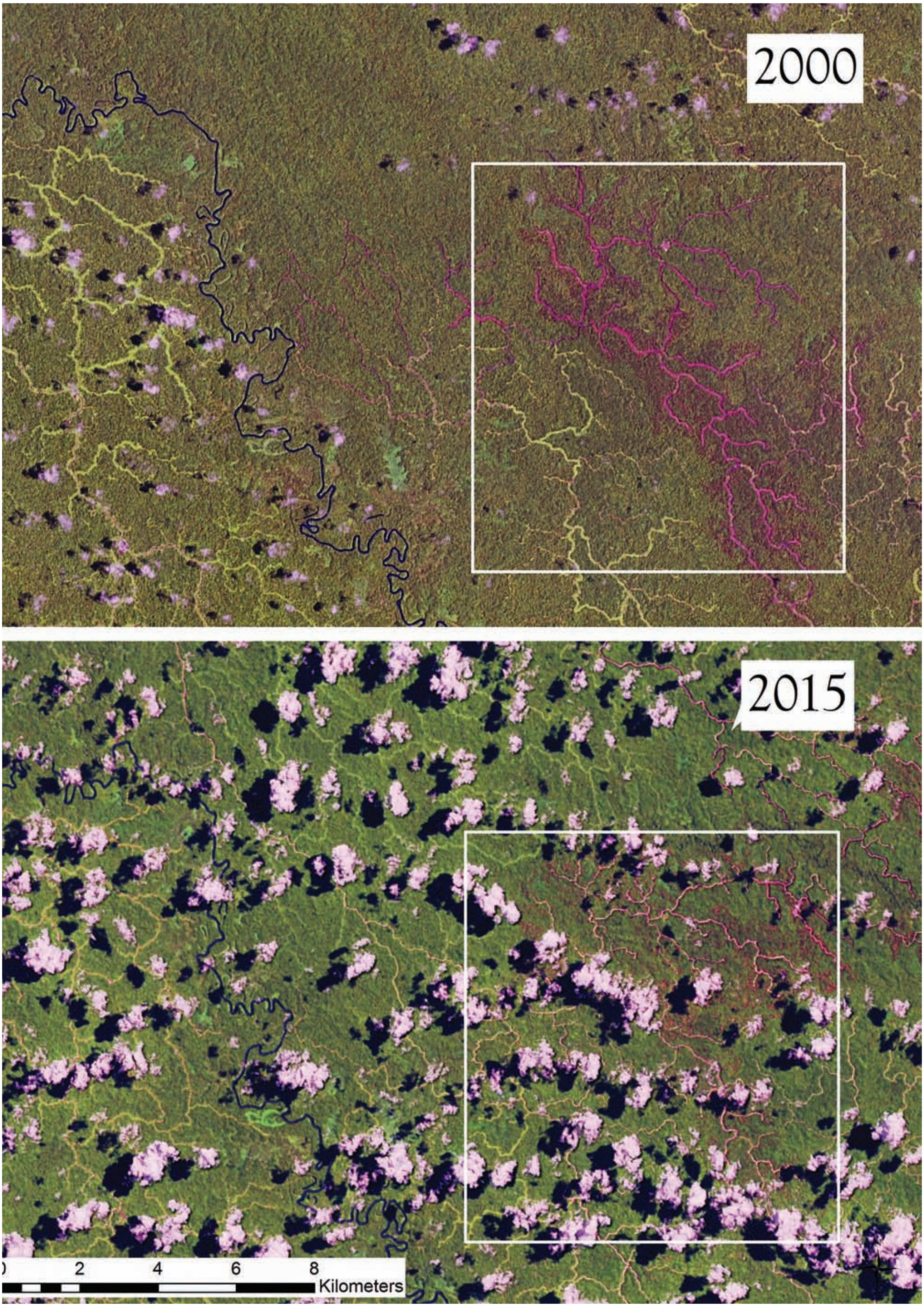

Figure 23. Repeat harvesting of the same forest within 15 years in the Wawoi Guavi Block 2 concession. The 2000 image is infra-red enhanced Landsat 7 recorded on 18 February 2000, active harvesting appears in pink/purple. The 2015 image shows the same area recorded on 8 April 2015 from Landsat 8. Active harvesting can again be seen in pink/purple.

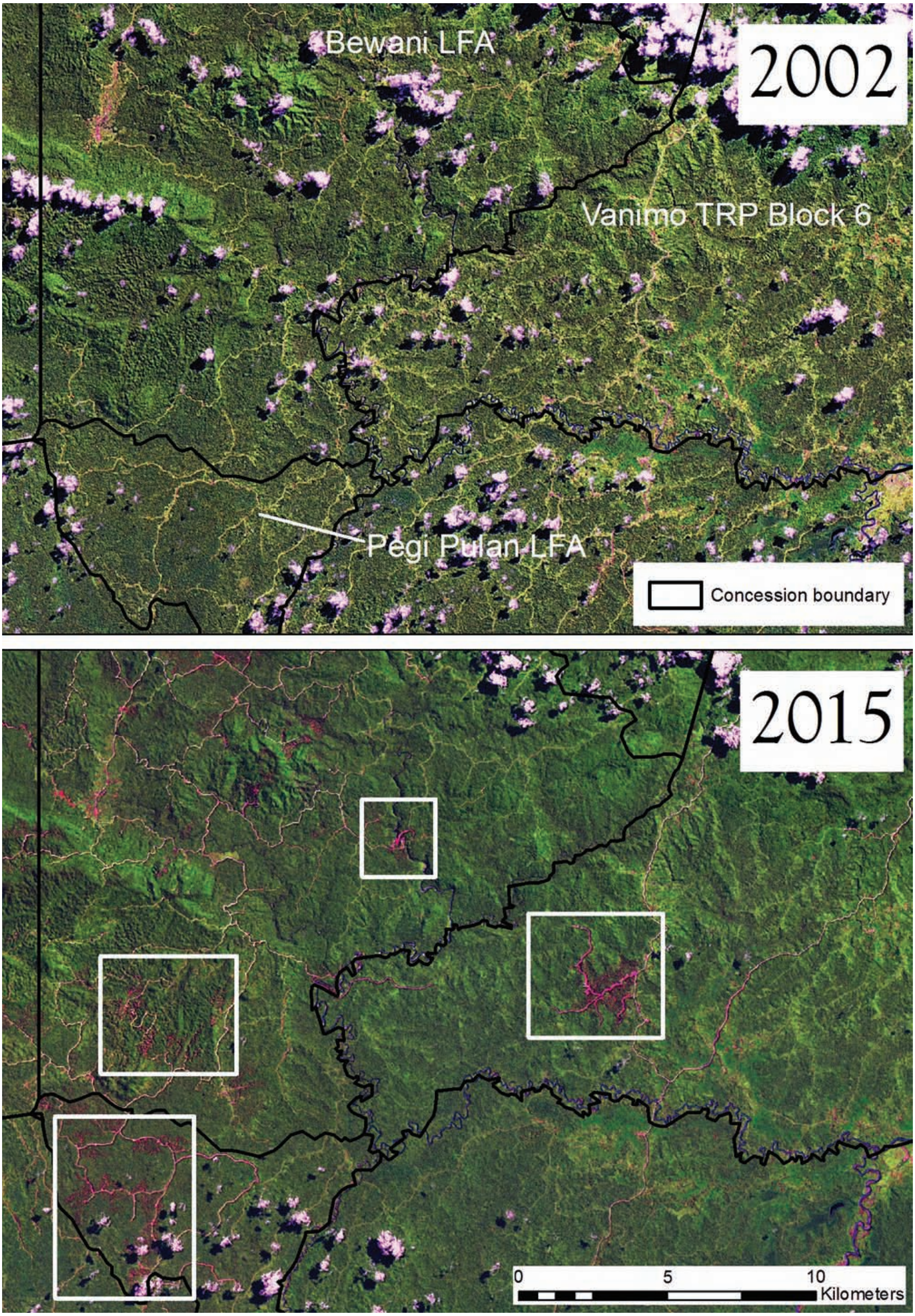

Figure 24. Re-entry logging within 35 years in the Bewani LFA, Vanimo TRP Block 6 and Pegi Pulan LFA logging concessions. The 2002 image was recorded on 21 May. Logging roads already cover the entire area. The 2015 image was recorded on 21 August and shows active harvesting in pink in all three concessions.

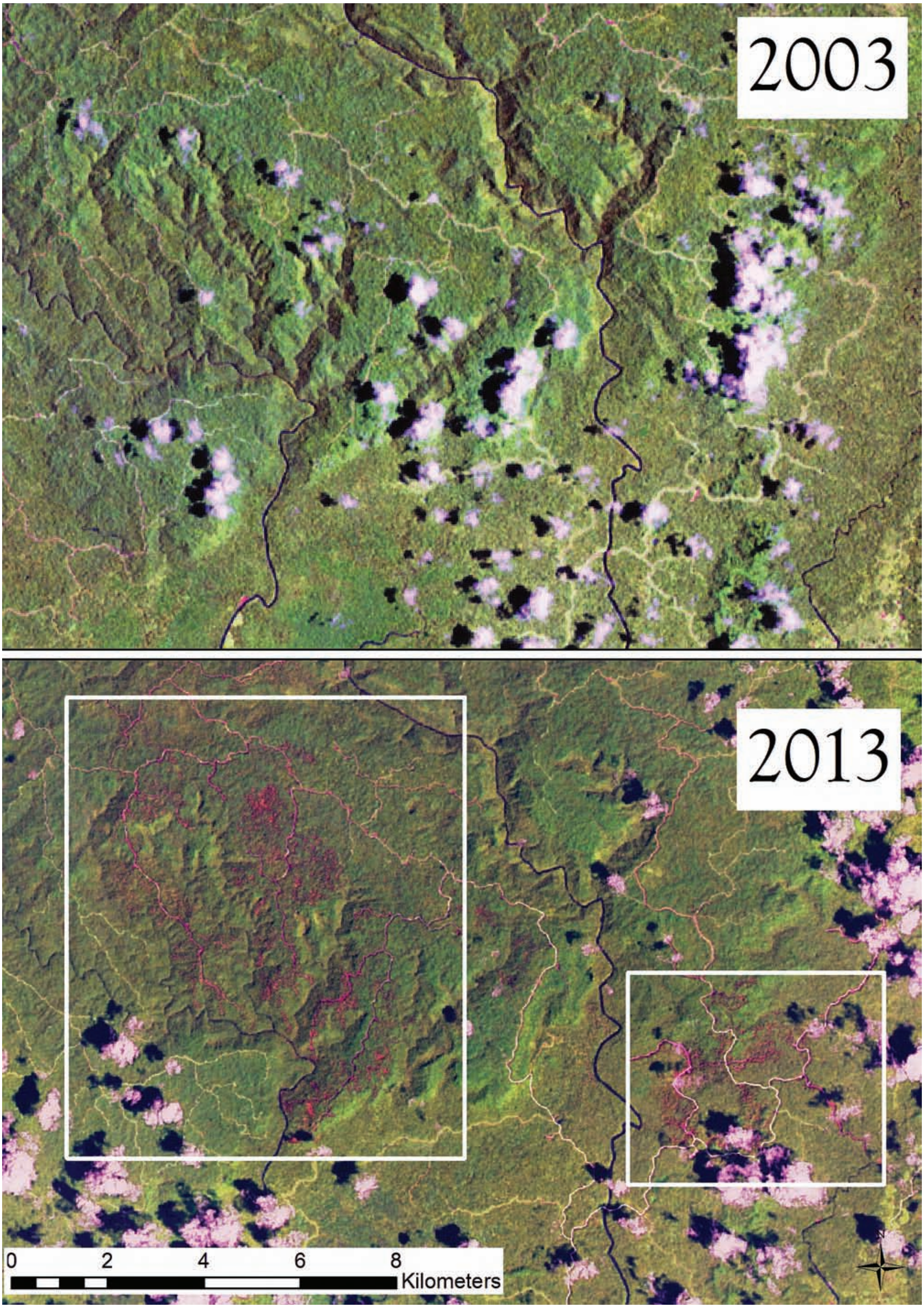

Figure 25. Repeat harvesting of the same forest within 35 years in the East Arawe concession, West New Britain. The whole area was unlogged in 1989. The 2003 image was recorded on 2 March 2003 - the whole area has been logged. Logging roads can be seen in light green/yellow. The 2013 image shows the same area recorded on 18 December 2015. Active harvesting can again be seen in pink/purple.

1.6.2 Remaining timber stocks in PNG's logging concessions

The intent of the PNG logging concession system is to maintain forests for timber production in perpetuity. However, widespread repeat harvests within the mandated 35 year period means that regeneration of timber stocks in these regions are likely to be seriously compromised. Indeed, a harvest cycle of 35 years is too short a period to sustain wood production over time, even if re-entry logging had not occurred (Sist *et al.*, 2003, Sist & Ferreira 2007, Putz *et al.*, 2008, Putz *et al.*, 2012). Progressive damage is done to forest structure and species composition if repeated harvests occur within too short a time period. This is a key area of concern for forest management in PNG.

Part of the reason why re-entry logging has been widespread is that logging concessions have been allocated an overly generous annual allowable cut (AAC). Each concession's AAC is measured as the total volume of timber (m^3) permitted to be harvested per year. No annual area limit is applied. The overestimation of how much saleable timber that is contained in PNG's forests when combined with the overestimation of the area of accessible forests within concessions, has long been an issue, and has resulted in overestimation of AACs. It has meant that in order to reach the annual volume allocated under the AAC, a much greater area than 1/35th of the concession has often been logged and a second round of harvesting then occurs in too short a time period.

It is timely therefore to estimate how much timber likely remains in PNG's logging concessions. Given the repeated harvesting of logged forests these forests should be excluded from any further logging in the foreseeable future to allow adequate regeneration. For this reason only unlogged commercially accessible forests are considered here as available for logging. Typically, first harvests in PNG's rainforests produce no more than 10-20 m^3 ha^{-1} of saleable timber (Shearman *et al.*, 2008, Bryan *et al.*, 2010, Bryan 2012). Hence an average of 15 m^3 ha^{-1} was used to assess remaining timber volumes (Table 4)[5]. Upper and lower estimates based on harvest intensities of 20 and 10 m^3 ha^{-1} respectively can be found in Annex 2.

The largest remaining contiguous unlogged block of lowland forest is located in Western province, and falls within the proposed Kamula Doso logging concessions. Allocation of Kamula Doso as a logging concession has long been disputed (see section 1.6.3 below). If Kamula Doso is not ultimately allocated to the logging industry, then PNG's remaining timber volumes would be substantially lower. For this reason, estimates of remaining timber volumes if Kamula Doso was to be excluded were also calculated.

Table 4 shows that if Kamula Doso is included, PNG has approximately 98.6 million m^3 of commercially accessible timber remaining in logging concessions. To maintain a 35 year cutting cycle, this indicates that PNG should be producing no more than 2.8 million m^3 per year, none of which should be coming from logged forests. If Kamula Doso is not included, then PNG has 88.1 million m^3 remaining in logging concessions, and PNG should be producing no more than 2.5 million m^3 per year. Yet in 2014, PNGFA estimates total timber production as 4.6 million m^3. This is 1.6 times more than should be occurring if Kamula Doso is included, or 1.8 times as much if it is not. A priority for forest management in logging concessions should be to reduce timber production in the majority of concessions and immediately exclude logged forests from repeat harvesting.

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[5] Full methods for calculating timber volumes are shown in Annex 1.

Table 4. Remaining timber volumes in PNG's logging concessions assuming an average harvest intensity of 15 m^3 ha^{-1}.

Province	Remaining timber volume 2014 (m^3)
Western (including Kamula Doso)	38,193,047
Western (excluding Kamula Doso)	(27,651,685)
Gulf	12,925,500
Central	3,995,100
Milne Bay	2,148,967
Oro	6,535,594
Morobe	1,263,376
Madang	4,883,627
East Sepik	2,280,091
West Sepik	11,119,687
Mainland coastal region	**83,344,989**
Mainland coastal (excluding Kamula Doso)	**(72,803,628)**
Southern Highlands / Hela	3,756,005
Enga	210,000
Western Highlands / Jiwaka	767,630
Chimbu	0
Eastern Highlands	0
Highlands region	**4,733,635**
Mainland total	**88,078,624**
Mainland (excluding Kamula Doso)	**(77,537,263)**
Manus	717,000
New Ireland	815,592
East New Britain	2,652,000
West New Britain	5,619,000
Bougainville	735,644
Islands region	**10,539,236**
TOTAL PNG	**98,617,860**
TOTAL PNG (excluding Kamula Doso)	**(88,076,498)**

1.6.3 The Kamula Doso logging concessions

One major uncertainty with the estimate of remaining timber stocks in PNG logging concessions is whether or not the Kamula Doso logging concessions are included in these projections. This huge and unique region is located in Western province, and its forests remained largely intact (Figure 26). The Kamula Doso rainforests are roughly the same size as the entire rainforest area in the Wet Tropics region in Queensland, Australia.

Kamula Doso had been plagued by controversy. The region was originally allocated by PNGFA as a logging concession to be operated by the Malaysian company Rimbunan Hijau. However, the legality of the process used to allocate this area was challenged in court on behalf of local landowners at the beginning of 2006 (Bryan 2012). The court found in favour of the landowners, declaring the allocation process unlawful and the allocation of Kamula Doso as a logging concession null and void. However, despite the area being the subject of a dispute in the courts, in 2008, the then PNG Office of Climate Change and Carbon Trading (OCCCT) issued ownership of one million tonnes of carbon credits within Kamula Doso to a company under the 'Reduced Emissions from Deforestation and Degradation' (REDD) initiative (Bryan 2012). This would have allowed for the sale of the carbon credits on the international carbon market, on the basis that carbon stored in Kamula Doso's forests would not be released through clearing or logging. At the time there was no legal basis for the OCCCT acquiring and allocating forest carbon rights and the entire OCCCT was later disbanded after a series of carbon trading related scandals (Bryan, 2012).

In addition to simultaneously being allocated as a logging concession, and as a REDD initiative intended to prevent logging by two different government departments, a third initiative had also allocated the Kamula Doso logging concessions as a Special Agriculture and Business Lease (see section 1.4 above). In the recent past the PNGFA has started a fresh process of allocating Kamula Doso to the logging industry.

The Kamula Doso region remains the biggest remaining expanse of intact lowland rainforest in PNG, and indeed one the region's largest remaining intact regions of primary lowland rainforest. As such it is of considerable ecological importance globally, both for plant and animal biodiversity, as well as its role in maintaining regional weather systems.

At the 2015 United Nations conference on climate change held in Paris (COP21), the PNG Government announced it would set aside millions of hectares of forests under the REDD initiative. The intent of REDD is to reduce carbon emissions by preventing or reducing deforestation and forest degradation, and thereby preserving the carbon stored in forests.

The forests inside the Kamula Doso concessions store approximately 480 million tonnes of carbon dioxide equivalents, and logging of its commercially accessible forests would release about 155 million tonnes of carbon dioxide after the first harvest alone (not accounting for repeat harvests within 35 years, see Annex 1 for methods).

As the PNG Forest Authority is currently progressing Kamula Doso towards allocation to the logging industry, there is a clear and documented threat for the imminent release of this carbon dioxide through logging. By halting its allocation to the logging industry, and instead protecting the region as an avoided deforestation and degradation project under REDD, the PNG government could immediately, and easily achieve its aims stated at the UN COP21 meeting.

In Kamula Doso, the PNG Government has a unique opportunity to protect one of the last remaining intact ecological wonders of the world as well as fulfilling its new obligations to the United Nations Framework Convention on Climate Change (UNFCCC).

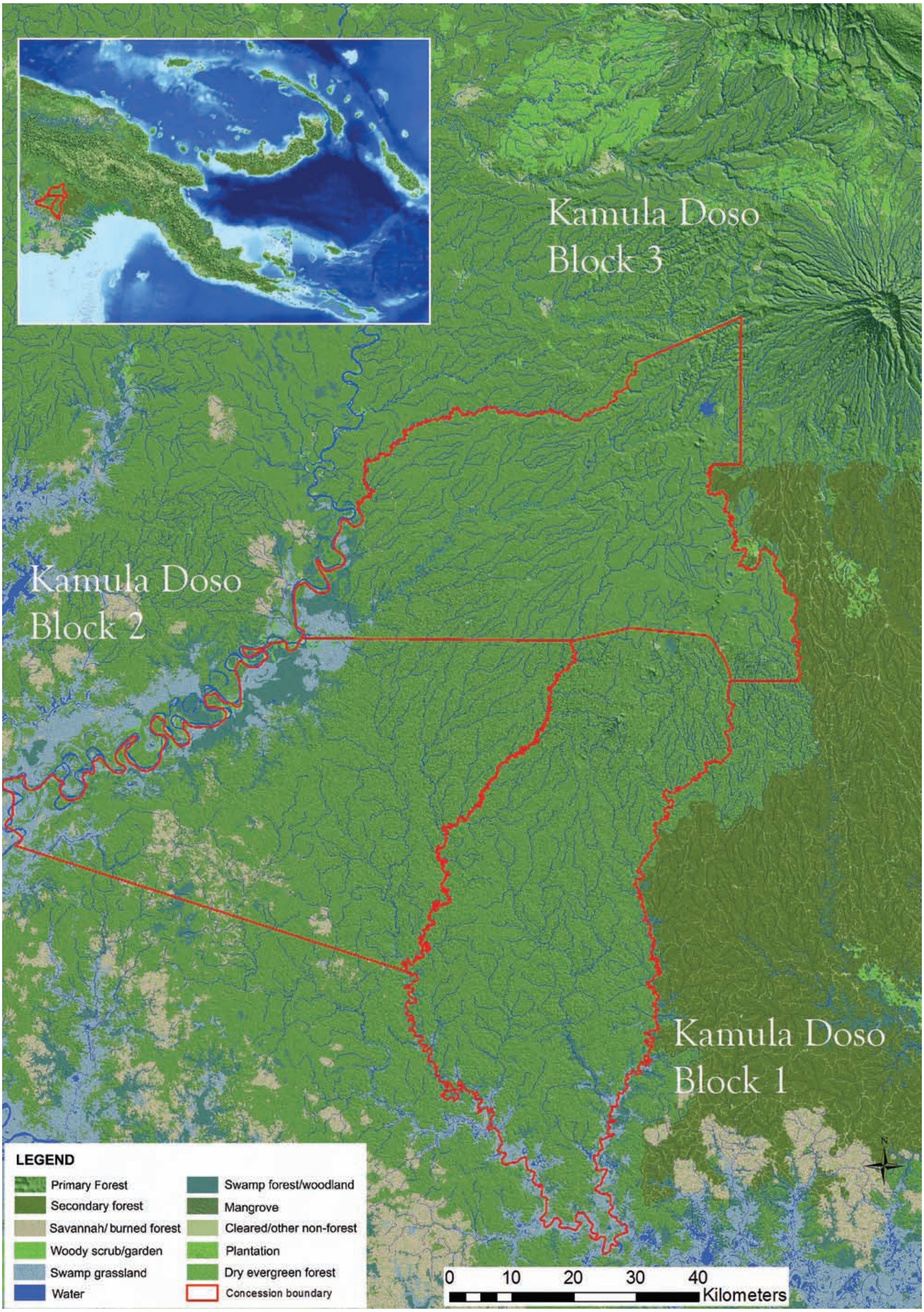


Figure 26. Vegetation in the Kamula Doso proposed logging concessions.

1.7 Fire in PNG's forests

When forests burn, large volumes of greenhouse gases are emitted into the atmosphere, and this exacerbates global warming. Forest fire is also a major driver of deforestation. In tropical rainforest natural burning rarely occurs - conditions are ordinarily too wet for this to happen. However during drought, rainforests can become desiccated making them more susceptible to burning (Nepstad *et al.*, 1999). Logged forests are more susceptible to drying out due to gaps left in the canopy after the removal of large trees, as well as edge effects from roads and the presence of large volumes of dry dead material (Nepstad *et al.*, 1999, Cochrane & Laurance, 2008). Hotter and dryer conditions during El Niño events increase the risk of rainforests being burnt. Large forest fires occurred in 1997/1998 during a major El Niño event, causing extensive deforestation and degradation.

In an effort to inform the public about the importance of fires in the management of PNG vegetation the UPNG developed a website to monitor where and when fires occur in the country (http://fire.pngsdf.com/). Fires are detected in near real time from instruments on board satellites orbiting Earth - these include the MODIS, OMI, AIRS, and MLS instruments. The location of fire hotspots are uploaded onto the website in near real time, and an archive of past fires since 1995 is also available. Fire detections occur over a 3 hour time period and each hotspot represents one detection over that period. The use of these data products comes courtesy of the Land Atmosphere Near-real time Capability for EOS (LANCE) system operated by the NASA/GSFC/Earth Science Data and Information System (ESDIS).

Figure 27. **Fires east of Kokoda, Central Province 2015. This fire was lit in alpine grassland but proceeded to burn within surrounding forests for two weeks.**

Data recorded from this initiative has made it possible to examine the role of fires in forest change over the period spanning 2002-2014. In total there were 81,819 fire hotspots detected across PNG during this period. In the course of each year there was a peak in burning during the dry season, usually between July and September, and far fewer fires over the wetter period. Fire occurrence over the period 2002-2015 is displayed in Figure 28. Although the forest change analysis in this study covered only up until 2014, fires detected in 2015 are also displayed for comparison for the reason that this year saw another major El Niño event and a massive increase in the number of fires can clearly be seen.

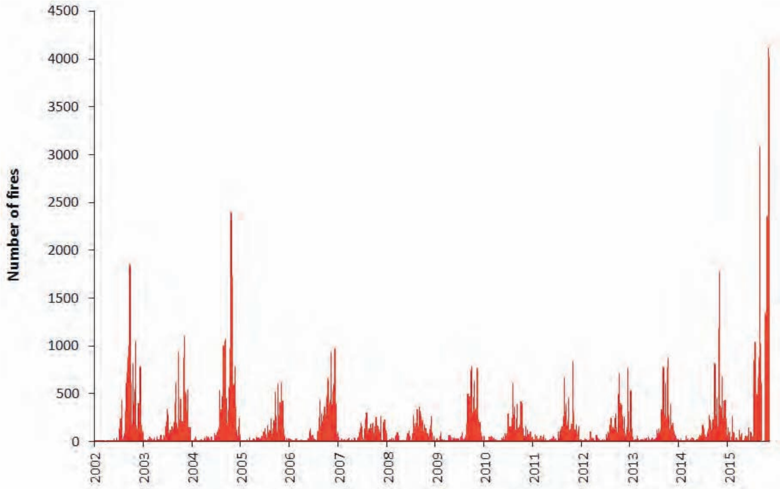


Figure 28. The number of fire hotspots in PNG recorded each week between 2002 and October 2015.

The period 2002-2014 did not see any strong El Niño events, and this is reflected in the lower number of fires. Eighty-six percent of all fires over this period occurred in non-rainforest vegetation. Only 6.7% of all recorded fires occurred in rainforest that was not cleared between 2002 and 2014. However, this situation was substantially different to what has occurred in 2015 which has seen a major El Niño event develop – 15% of all fires detected between January and October 2015 occurred in forests. This is likely due to the desiccation of forests as a result of hot dry conditions, making rainforests more susceptible to burning.

Between 2002 and 2014, the non- El Niño period, the dry evergreen forests and grasslands in the south of Western province were the zones of heaviest burning - as were the seasonally dry region near Port Moresby, the cleared and grassland regions of the Ramu valley, and the intensively farmed highlands valleys. The largest area of intact unlogged forest remaining in PNG is located in the wet lowlands of Western province, and it is there that there is a notable absence of fires.

Within those areas that were deforested between 2002 & 2014, 9% of fires occurred within active logging operations, 41% in agricultural plantations, primarily for the planting of oil palm, while 49% were non-forestry and non-plantation related (Figure 30). Many of these 49% of fires were due to burning of material to allow for shifting cultivation where fire is either lit deliberately to burn felled trees for new planting, or accidentally escapes from surrounding gardens into adjacent forest, causing unintentional deforestation.

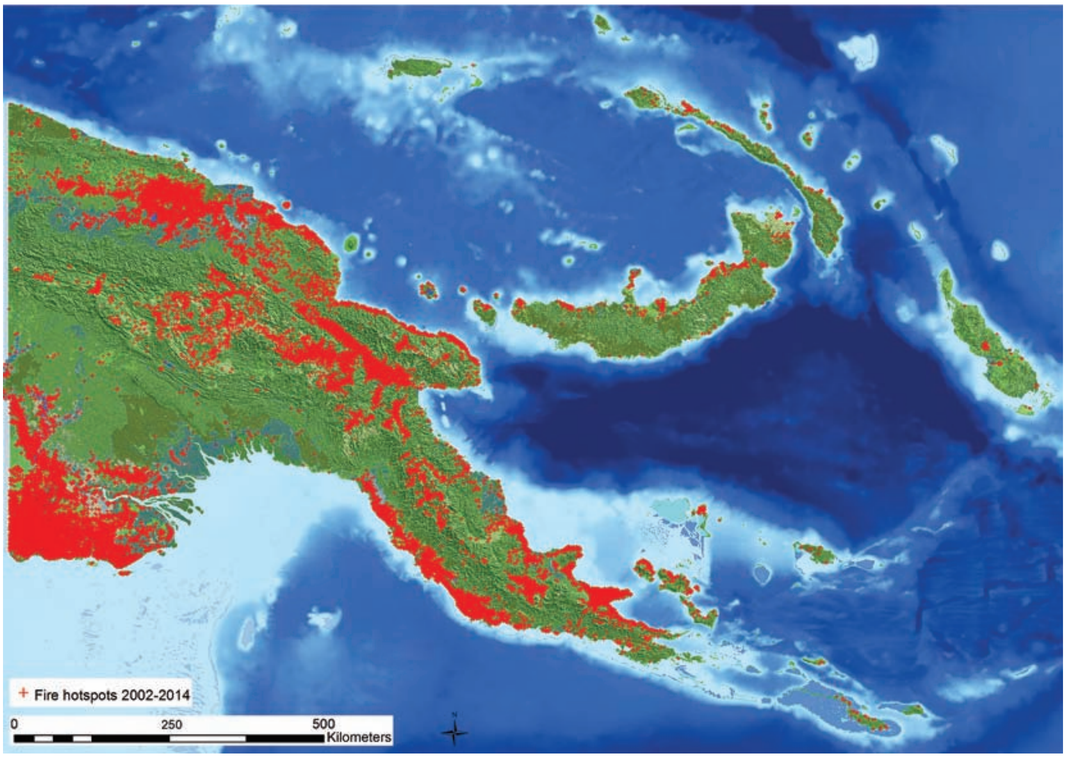


Figure 29. Location of fire hotspots recorded in PNG 2002-2014 – most occur in non-forest vegetation or in the savannah regions of the South Fly and Morehead Peninsula

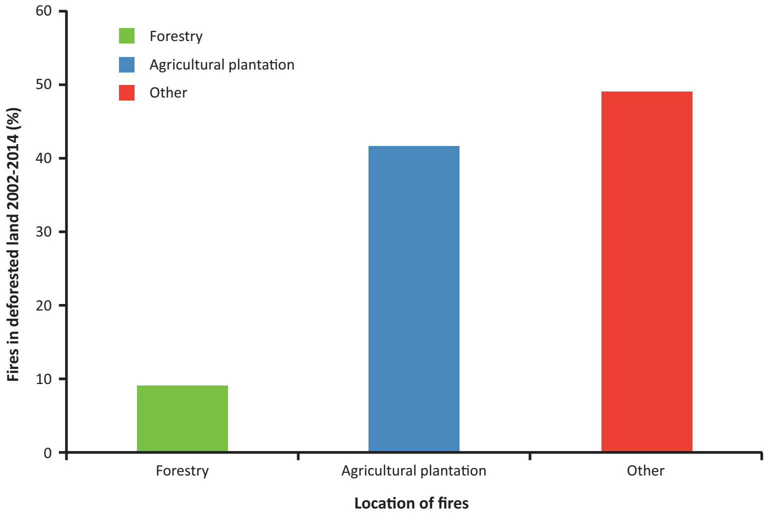


Figure 30. The location of fires in deforested land 2002-2014, land deforested as a result of forestry (roads, log ponds etc), for agricultural plantations, and for other non-forestry non-plantation reasons, primarily subsistence agriculture.

Figure 31a. Forest die back from a ground fire in the Owen Stanley ranges. Intact forest can be seen in the foreground in dark green, with patches of dead burned forest on the hillside.

Figure 31b. Extensive burning and fire-related forest die back near Mt. Strong, Morobe Province.

The locations of fires and people are very closely linked in PNG. Indeed within the period 2002-2014, 34% of all fires occurred within 1 km of a building. The number of fires declined dramatically and exponentially the greater the distance from human habitation (Figure 32). Seventy-six percent of all fires detected occurred within 6 km of a house or building. This strongly suggests that the majority of fires are started by people. Whilst the total area cleared as a result of fire between 2002 and 2014 was lower than in the previous decades, this strong link between agriculture, fire and deforestation is a growing concern.

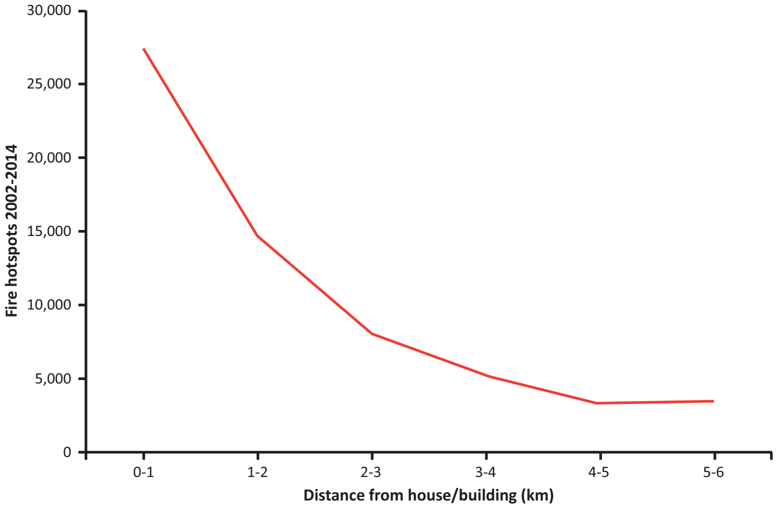


Figure 32. The number of fire hotspots 2002-2014 occurring within 6 km of a building in PNG. At least 75% of all fires occurred within 6 km of a building.

1.8 Summary

In the *State of the Forests of PNG 2002-2014*, changes in PNG's forests were documented. While this period saw an overall deceleration in deforestation compared to the earlier 1972-2002 period, the expansion of the industrial logging sector continued, and those forests accessible to the logging industry were degraded at a much higher rate than inaccessible forests. Of particular concern for the future of PNG's forests has been the allocation of 3.8 million hectares of rainforest in Special Agriculture and Business Leases, which allows for their future deforestation. While change within these areas was still relatively moderate, some of these leases saw substantial clearances for oil palm plantations. This signals that PNG may be on the cusp of a period of major deforestation for agricultural development, such as has occurred in Indonesia and Malaysia in earlier decades.

A further reason for concern for the future of forests is the significant burning of forest that has occurred in 2015 as a result of a major El Niño. Logged forests are at particular risk of fire-related deforestation in the coming years. A key issue for forest management in PNG is repeat harvesting of logged forests. As documented in this report, widespread repeat logging within 35 years has occurred in PNG's logging concessions, meaning that they are at increased risk of deforestation, and are unlikely to be the source of sustainable timber production into the future. These forests need to be allowed to fully regenerate over the coming decades. In addition, current timber production from logging concessions remains too high to maintain the 35 year cutting cycle, and ought to be reduced as a matter of priority.

In 2015, the largest remaining intact block of lowland rainforest in PNG is located in the Kamula Doso region, Western province. This area is under particular threat as it is currently being progressed towards allocation to the logging industry (as well as still being within an SABL). PNG stands at a cross roads. The current trajectory is to continue the expansion of logging into all available unlogged forests, continue to repeatedly harvest already logged forests in too short a time period, and then ultimately clear these forests for vast agricultural or timber plantations. This is the path that occurred in many parts of neighbouring Indonesia and Malaysia. Alternatively, PNG can choose to protect what remains, and reform unsustainable logging practices. Whether PNG's forests remain in future decades depends on this choice.

Chapter 2

Climate Science: The Case for a Rapid and Effective Policy Response

Will Steffen

Will Steffen is a Councillor on the publicly-funded Climate Council of Australia that delivers independent expert information about climate change, and is an Emeritus Professor at the Australian National University (ANU), Canberra. He is also an Adjunct Professor at the University of Canberra, working with the Canberra Urban and Regional Futures (CURF) program, and is a member of the ACT Climate Change Council. His research interests span a broad range within the fields of climate and Earth System science, with an emphasis on incorporation of human processes in Earth System modelling and analysis; and on sustainability and climate change, particular in the context of urban areas.

Climatic patterns are critical to the growth, health, and persistence of PNG's forests and the citizens of PNG who depend on forests for their livelihoods. The changes occurring to the global climate system are therefore of foremost importance to PNG. The understanding of the climate system, and of the influence of human activities on the climate, has advanced remarkably over the past few decades. This enhanced knowledge base constitutes a compelling case for urgent and effective action by nations around the world if we are to limit climate change to levels at which human societies can continue to develop and thrive. Three critical insights delivered by climate change science underpin this urgency for effective climate policy.

First, warming of the climate system is unequivocal. The average surface temperature of the Earth has risen significantly over the past century, and particularly since 1950 (Figure 33). The average temperature is now 0.9°C higher than its pre-industrial level. The decade of 2000-2009 was easily the warmest since modern temperature records began in the 1800s; it was significantly warmer than the 1990s, which were in turn warmer than the 1980s. There is other strong evidence of warming. The heat content of the ocean has risen steadily relative to 1961, when reliable measurements were first available (Figure 34). Global average sea level has risen about 20 cm since the 1880s, and the rate of increase has risen to 3.2 mm yr^{-1} for the 1993-2009 period (Figure 35). Arctic sea ice is diminishing, the large polar ice sheets on both Greenland and Antarctica are experiencing net losses of ice mass, and most glaciers and continental ice caps around the world have been in retreat over the last century. A warming signal is also evident in an increasing number of global observations of the responses of biological species and ecosystems.

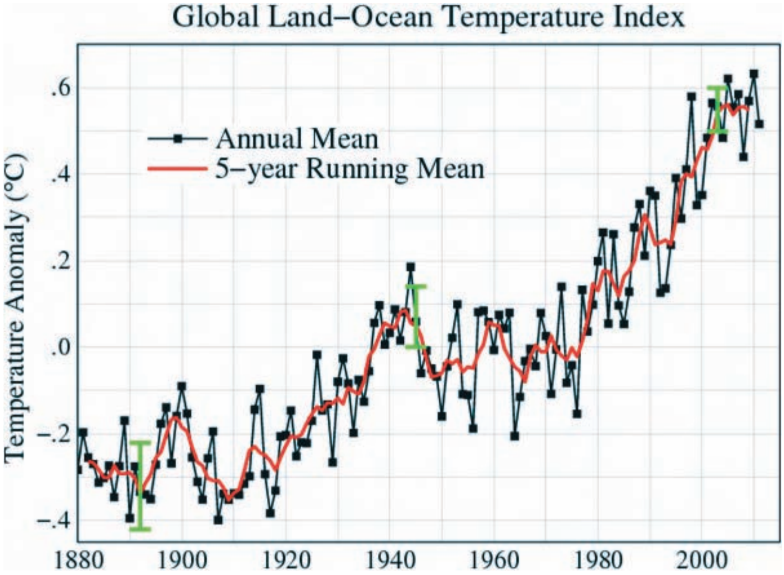


Figure 33. Temperature trend from the 1880s to the present, with the base period 1951-1980. *Source: NASA GISS Surface Temperature Analysis.*

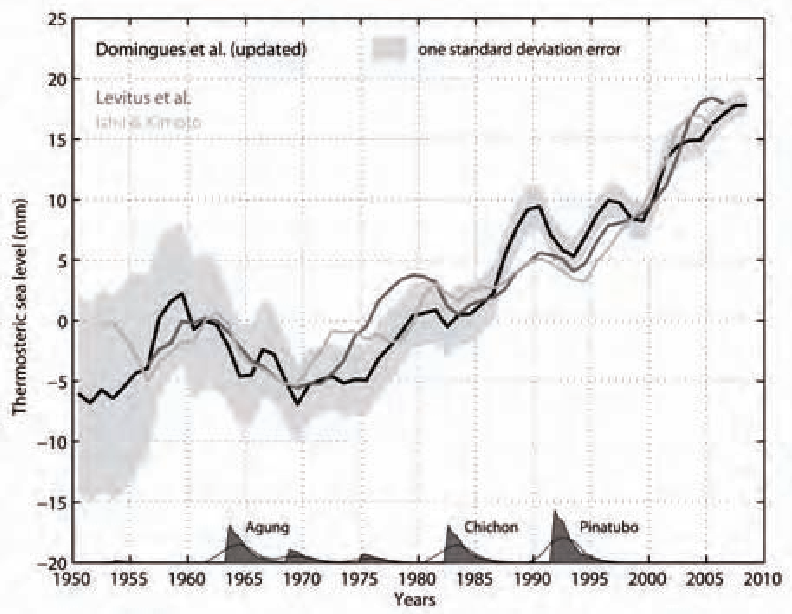


Figure 34. Updated estimates of ocean thermal expansion, a measure of ocean heat content. The updated Domingues *et al.* (2008) time series is shown in black, and one standard deviation uncertainty estimates are indicated by the grey shading. The estimates for Ishii and Kimoto (2009) and Levitus *et al.* (2009) are shown as light grey and mid-grey lines respectively. The estimated stratospheric aerosol loading (arbitrary scale) from the major volcanic eruptions is shown at the bottom. *Source: Church et al. (2011).*

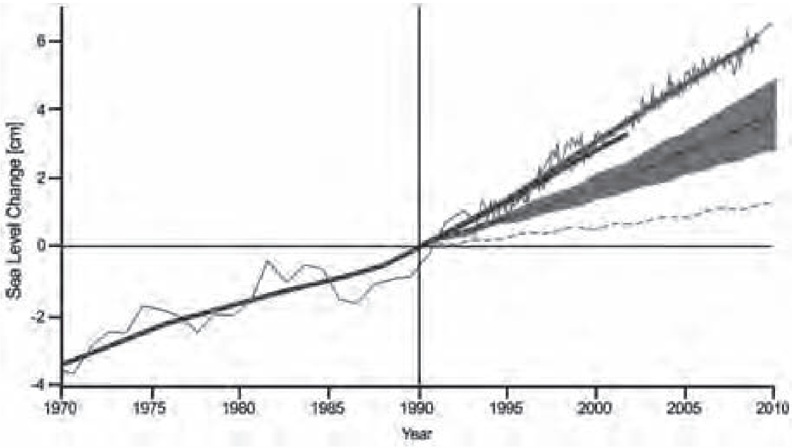


Figure 35. Sea-level change from 1970 to 2008. The light grey line from 1970 to 2002 is based on tide gauge data, and the heavy black line is the running mean. The jagged, light grey line from 1993 to 2008 is based on satellite data and the heavy grey line is the running mean. The envelope of IPCC projections (broken lines from 1990) are shown for comparison. *Source: after Rahmstorf et al. (2007), based on data from Cazenave and Narem (2004); Church and White (2006), Cazenave (2006) and A. Cazenave for 2006–08 data.*

Second, it is beyond reasonable doubt that human activities, primarily the emission of greenhouse gases, are responsible for most of the observed warming since the middle of the 20th century. The physics by which greenhouse gases affect the energy balance at the Earth's surface and thus the climate have been understood since the 19th century, with a vast amount of experimental and observational research in the 20th century strengthening this understanding. Climate models can only simulate the observed temperature increase over the 20th century up to the present if they include the human emission of greenhouse gases, primarily carbon dioxide, in addition to natural factors such as volcanoes and changes in solar radiation. There are other "fingerprints" of greenhouse gas-induced warming – for example, winters are warming more rapidly than summers and overnight minimum temperatures have risen more rapidly than daytime maximum temperatures – that confirm the human causation of the warming trend.

Over 80% of the additional carbon dioxide in the atmosphere since the industrial revolution has come from the burning of fossil fuels, primarily in the wealthy countries. The remainder has come from deforestation. Thus, the most effective ways to slow and constrain climate change are to quickly and deeply cut fossil fuel emissions and to eliminate deforestation.

In terms of human causation, Papua New Guinea is a very small contributor to the problem in terms of both aggregate emissions and per capita emissions of greenhouse gases. The most important role that PNG plays in the climate system is through its extensive, carbon-dense tropical forests. The advent of the REDD approach (Reducing Emissions for Deforestation and Forest Degradation) offers an excellent opportunity for PNG to benefit from this resource. The science of the carbon cycle clearly supports the REDD approach, as it shows that primary, undisturbed forests store the maximum amount of carbon for a given soil type and climate regime. Thus, protecting PNG's primary forest estate, and allowing secondary forests to fully regenerate, would make a significant contribution towards stabilising the climate system that would prevent the worst of the potential impacts from eventuating.

Third, the risks of climate change for human well-being and for the ecosystems on which humanity depends are already observable, and the risks of further impacts on human well-being rise sharply as the climate system warms further. Climate change is altering the fundamental life support systems that human societies depend upon. Food production is highly influenced by climate, and those countries most vulnerable already to weather and climate instabilities – mostly in the tropics – are predicted to suffer the most from climate change. As the water cycle intensifies, rainfall patterns are changing, leading to changes in the availability of water at local and regional levels. Impacts on economies from a changing climate are potentially very severe, including damage to infrastructure, loss of livelihoods and erosion of primary industries. Human health is the ultimate integrator of climate change impacts, and threats to health are complex and numerous. They range from direct threats from the stress of higher temperatures to the more indirect threats arising from the changing environment for infectious disease vectors and the increased vulnerability to disease that arises from the deterioration in the quantity and quality of food and water.

Many of the more immediate risks are associated with extreme weather events, which are a natural feature of the climate system. Some of these extreme events, however, have become more probable with the rising trend in average global temperature (Figure 36). Examples include (i) heat waves, such as those experienced in central Europe in 2003 and in Moscow and Melbourne in more recent years, with significant impacts on human health and well-being and on agricultural production; and (ii) coastal flooding events, which in some parts of the world have become more frequent with the modest levels of sea-level rise that have already occurred.

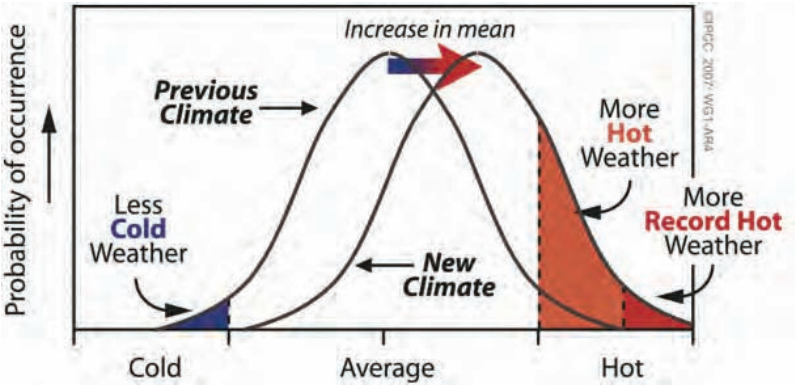


Figure 36. Relationship between means and extremes, showing the connection between a shifting mean and the proportion of extreme events, when extreme events are defined as some fixed threshold related to a significant impact (e.g., heatwave leading to excess deaths).*Source: IPCC (2007).*

The risks of climate change for Papua New Guinea share many features of the risks experienced around the world. PNG's climate will continue to warm, leading to an increasing probability of high temperature days, and to sequences of high temperature days and nights (heat waves). The latter pose significant risks for people living in urban areas such as Port Moresby, with higher risks for the more vulnerable people in society – infants, the elderly and those with low incomes and thus less access to medical care. Higher temperatures can also affect human health through changes in the conditions for disease vectors, for example, the potential for the range of malaria-carrying mosquitoes to rise to higher elevations.

A warming climate results in an intensification of the hydrological cycle. There is some evidence globally that the amount of water vapour in the atmosphere has increased over the past three decades, primarily in response to rising sea surface temperatures in most ocean basins and thus an increase in evaporation. This trend is especially prominent in the tropics, where an increase in the saltiness of the surface waters is evidence of an increase in the evaporation rate.

More importantly in terms of impacts that affect societies, the increased rainfall is predicted to lead to more intense rainfall events, a trend that may already be occurring according to the evidence available. This has important implications for PNG, where those settlements already prone to flooding are likely to experience more frequent and more severe flooding in future. Agriculture on steep land will also be at risk of increased erosion, and infrastructure, such as that for transport and mining, will also be at risk of increased disruption.

The effect of climate change on tropical cyclones is not clear. There is no observational evidence yet to show any changes beyond natural variability in either the frequency of cyclones or their storm tracks. There is some evidence, on the other hand, for a possible link between high sea surface temperatures and increased cyclone intensity, although there are some significant questions surrounding the reliability of the observational data and the short period over which data is available. Most climate models suggest a modest increase in cyclone intensity by the end of this century.

An aspect of climate change with particular significance for PNG is sea-level rise. As noted above, sea-level is currently rising at a globally averaged rate of 3.2 mm yr^{-1}, which large variations in regional and local rates. Projections for the additional rise over the 21st century range from about 0.5 m to 1.0 m, with a few somewhat higher. This may seem like a modest amount (less than the height of an average adult human), but even a small increase like 0.5 m can lead to large multiplication factors for "high sea-level events" – coastal flooding that occurs with a high tide and storm surge. In some locations, a current 1-in-a-100 year flooding event could occur every year, or even every month, with an 0.5 m sea-level rise.

Increased coastal flooding could also be triggered by the projected increase in intense rainfall events, coupled with a high tide and storm surge, and exacerbated by the slow but steady increase in sea level. In general, those areas of the coast that are already prone to flooding will be most vulnerable to this type of synergistic effect between rainfall and sea-level rise.

Ocean acidification was, until recently, a "sleeping giant" in the field of climate change impacts. About 25-30% of the additional carbon dioxide emitted to the atmosphere by human activities is absorbed by the oceans. The carbon dioxide reacts with water to form carbonic acid, with deleterious effects on marine organisms, especially those that form calcium carbonate shells. Much of the focus to date has been on coral reefs, but some important species of plankton, as well as molluscs and crustaceans, are also vulnerable to increasing ocean acidity. The ultimate effects on organisms higher up the food chain in marine ecosystems, on which many coastal communities in PNG rely for protein, are largely unknown but likely to be significant.

In summary, the case for action on climate change is both compelling and urgent. Most countries around the world have agreed to limit climate change to a temperature rise of no more than 2ºC above the pre-industrial level, to avoid the worst of the impacts. This means that the global greenhouse gas emission trend, currently strongly upward, will need to peak and be on a strongly downward trend by the end of this decade at the latest. As Figure 37 shows, the longer we wait, the more difficult the task becomes. If global emissions peak in 2015, then the maximum rate of reduction thereafter is 5.3% per year, difficult but not impossible. But if global emissions don't peak until 2020, the maximum rate of reduction thereafter is 9.0% per year, virtually impossible. This is the critical decade for action. As noted above, PNG has the opportunity to contribute its share towards stabilising the climate system by protecting its large, carbon-rich forest estate.

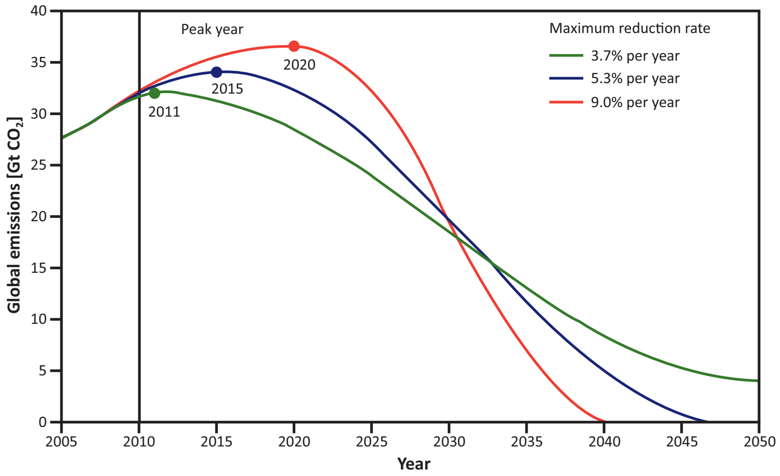
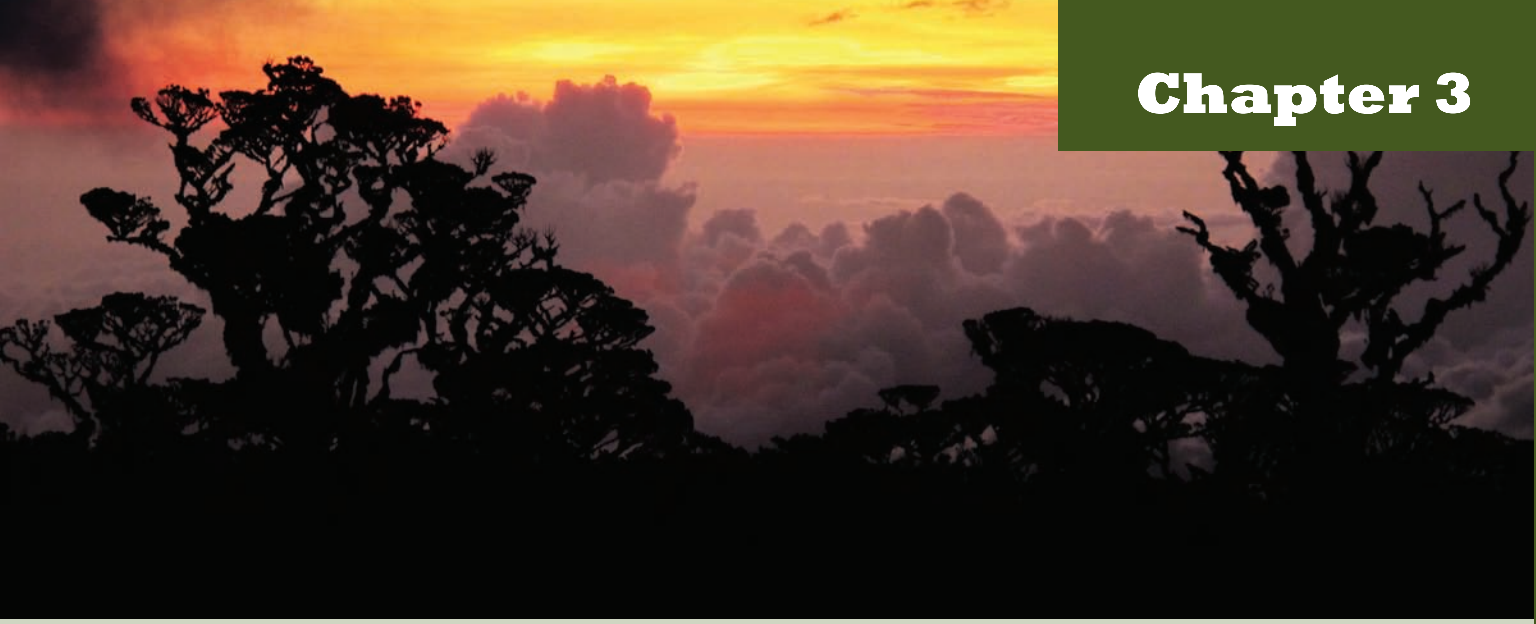


Figure 37. **Three emission trajectories based on the budget approach and giving a 67% probability of meeting the 2°C guardrail.** *Source: WBGU (2009).*



Chapter 3

Large-scale climatic significance of Papua New Guinea forests

A. M. Makarieva & V. G. Gorshkov

Victor Gorshkov holds position of leading researcher in the Theoretical Physics Division of Petersburg Nuclear Physics Institute in Russia. Victor was educated as theoretical physicist at the University of Leningrad, Russia. Between 1958 and 1970 Victor worked in Leningrad Physical and Technical Institute, then until now in Petersburg Nuclear Physics Institute. Victor's research interests evolved from atomic physics, quantum electrodynamics and high energy physics to theoretical investigations of the physical and biological principles of life stability. Between 1978 and 1998 Victor was lecturing in Leningrad Politechnical Institute on ecological physics. Victor's main scientific challenge is to quantify the stabilizing impact of the natural ecosystems on Earth's environment and climate.

Anastassia Makarieva holds position of senior researcher in the Theoretical Physics Division of Petersburg Nuclear Physics Institute in Russia, where she works since 1996 when she graduated as biophysicist from the Leningrad Politechnical Institute in Russia. In 2000 Anastassia got her PhD in atmospheric physics. Together with Victor Gorshkov in 2007 Anastassia formulated the concept of the biotic pump of atmospheric moisture. In 2008 Anastassia got the L'Oreal-UNESCO-Russian Academy of Sciences Prize "For women in science". Currently Anastassia's research focuses on quantifying the impact of forests on the continental water cycle. She is also interested in developing a cross-disciplinary theoretical framework for assessing the problem of environmental stability on Earth.

Abstract

The "Maritime Continent" describes the island archipelagos and surrounding waters of the tropical Southeast Asia-Pacific region. The Maritime Continent, of which Papua New Guinea is a significant part, is situated in a unique climatic region of the Earth. Here precipitation is exceptionally high even compared to other rainy near-equatorial regions of the world. High rainfall in the warm tropical climate is key for the country's high agricultural productivity and the well being of PNG people. This chapter explores how PNG forests contribute to the maintenance of this favorable climatic regime and how their devastation could trigger adverse changes in the local, regional and possibly global climates. It is also discussed how meteorological data gathering and analysis in PNG is crucial for quantifying the climatic impact of PNG forests and how these analyses can help address some of the major challenges of modern atmospheric science to improve the credibility of climate and weather forecasting under globally changing conditions.

Introduction

The greatest treasure of Papua New Guinea is its environment: a warm climate with abundant sunlight and rainfall and high biological productivity are exceptionally favourable for human life. In these hospitable conditions humans have been thriving in PNG for over forty thousand years (O'Connell and Allen, 2004). Likewise the overwhelming majority of modern population of PNG – more than 85% – still depend in their daily life on subsistence farming and other biological products provided by natural ecosystems (Ramakrishna and Bang, 2015). Recent advances in science reveal that natural forest ecosystems play a far greater role in shaping the regional and global climatic conditions than previously thought (Sheil, 2014). For example, latest research established how organic compounds emitted by the forest canopy control the formation of atmospheric aerosols that trigger cloud formation (Riccobono *et al.*, 2014). New evidence is actively discussed that water vapor evaporation by plants may represent the dominant part of the total water vapor flux from the Earth's surface on land, especially in highly productive forests (Jasechko *et al.*, 2013; Schlaepfer *et al.*, 2014). Both theoretical studies and data analyses highlight the importance of forests for continent-scale import of moisture (Makarieva *et al.*, 2013a, 2014b; Andrich and Imberger, 2013; Poveda *et al.*, 2014). There is an increasing recognition that natural forests are not merely impacted by climate change but are themselves active players in regional climates (Lawrence and Vandecar, 2015). Large-scale shifts in natural vegetation cover associated with deforestation can trigger adverse climate impacts which will hit local nations in the first place and may also have long-ranging distant impacts.

In this chapter we first discuss the physical and ecological mechanisms by which forests impact the regional water cycle. We then consider how forest is an ultra-complex solar-powered biochemical machine which, as it functions, processes enormous fluxes of environmental information. These fluxes are significantly beyond the information processing capacity of modern civilization. If lost, the regulatory climatic functions of natural forests cannot be replaced by a technology. We continue with a discussion of the patterns of atmospheric dynamics that shape PNG climate and how the forests play in with their regulatory potential. Finally, we analyze the current and possible future impacts of deforestation on the climate in PNG as well as their large-scale implications.

For nations like PNG that uniquely remain in possession of vast amounts of natural forests, it is vital to be on the frontline of investigating their climatic significance as well as the critical stability thresholds. During the last two decades PNG was faced with a declining annual rainfall and saw an unprecedented drought (As-syakur *et al.*, 2013; Spinoni *et al.*, 2014). As new studies reveal how forests impose control on the regional water cycle, the continuing deforestation in PNG emerges as a major threat to environmental stability (Figure 38). This highlights the need for a national strategy of forest conservation as a major pillar of climate stability for the modern and future generations of PNG people.

PNG is situated in a climatic zone that is of crucial importance for the Earth's climate as a whole. It is situated in the rising branch of the Walker circulation which brings moisture from the eastern part of the tropical Pacific ocean to the Maritime Continent. The Maritime Continent refers to the island archipelagos and surrounding waters of the Southeast Asia-Pacific region, including Indonesia, the Philippines, Papua New Guinea, parts of Malaysia and Brunei. As the latest studies suggest, this circulation may be key to understanding the dynamics of global surface temperatures. The recent decadal pause in global warming can be related to an accelerated heat intake by the Pacific ocean, which has to do with some changes in the Walker circulation (England *et al.*, 2014). Since the Walker circulation depends on the localization of rainfall, any large-scale changes in evaporation regimes over the Maritime Continent resulting from deforestation may thus have a profound impact on the global climate. This once again emphasizes the importance of meteorological data gathering and analysis to quantify the climatic impact of PNG forests.

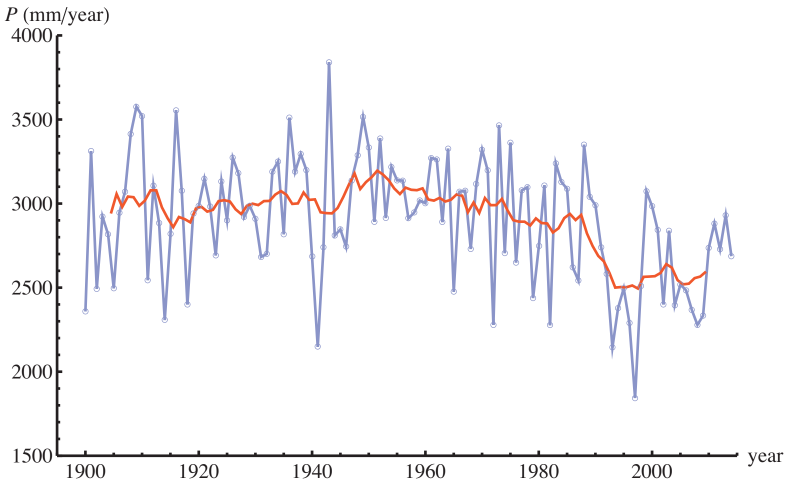


Figure 38. Long-term annual rainfall trends on the Papua Island according to the University of Delaware terrestrial precipitation database of Matsuura and Willmott (2015). The red line shows 10-year moving average. The long-term mean for 115 years from 1900 to 2014 is 2.9±0.4 mm/year. The declining trend in 1998-2010 in PNG is consistent with satellite data from the Tropical Rainfall Measurement Mission (TRMM) (see As-syakur *et al.*, 2013, their Fig. 10).

Forests and the water cycle on land

Terrestrial water budget

Water on land is not a secure resource. As landmasses are elevated over the ocean, they are continuously losing liquid water. Under the action of gravity water runs down the continental slopes towards the ocean. The global river runoff and global water storage in the soil horizon are estimated, respectively, at 37×1012 m^3 $year^{-1}$ and 122×1012 m^3 (Dai and Trenberth, 2002; Webb *et al.*, 1993). This means that if the global moisture import from ocean to land stalled, the modern river runoff would have depleted the soil moisture store on land in less than four years (L'vovitch, 1979). Thus, a persistent transport of moisture back from the ocean to land must exist for land to remain moistened.

Calculated per unit area of the Earth's continental surface (149×1012 m^2), the above estimates correspond to an average soil moisture store of M = 820 mm and river runoff of R = 250 mm $year^{-1}$. The moisture store in the soil horizon of Papua New Guinea is close to the global average ranging from 600 to 1200 mm (Webb *et al.*, 1993, their Fig. 3a). Meanwhile the river runoff in Papua New Guinea is nearly one order of magnitude higher than the global mean: it is estimated at about 2000 mm $year^{-1}$ (Hall, 1984; Milliman and Farnsworth, 2011). For example, despite their relatively small drainage areas two of Papua New Guinea's rivers, Sepik and Purari, are among world's largest 50 rivers by discharge (Dai and Trenberth, 2002). Thus the river runoff in PNG can deplete the store of moisture in the upper metre of the soil horizon – about 300 mm for volumetric water content of 30% (Hartemink, 2007) – in less than two months! This illustrates that the soil moisture store in PNG is exceptionally fragile and ephemeral. The water cycle in PNG owes itself to an intense moisture import via the atmosphere (Figure 39).

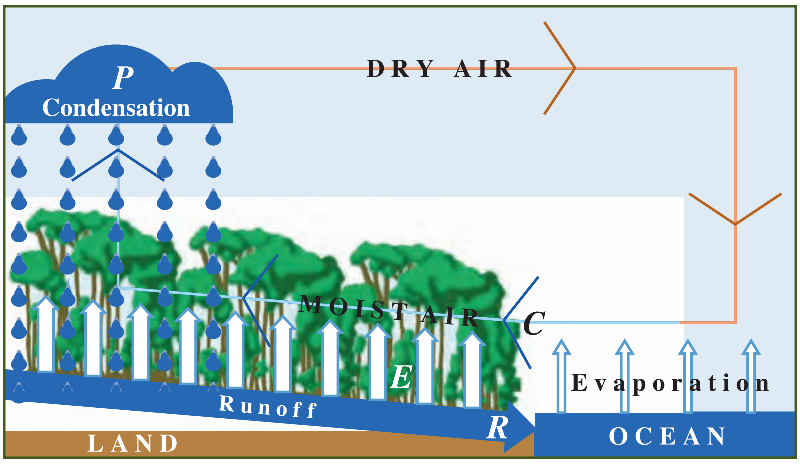


Figure 39. The water cycle on land. Evaporation from the ocean (thin white arrows) enriches low-level air with water vapor. Moist air arrives to land where the water vapor amount in the air grows even further owing to evaporation E from the forest canopy (thick white arrows). As moist air ascends and cools over the forest, water vapor condenses and falls out of the air forming precipitation (P). Liquid water returns to the ocean as river runoff R: this flux is equal to atmospheric moisture import C. Dry air completes the cycle: it returns to over the ocean in the upper atmosphere and descends.

Precipitation P increases the store of liquid water on land, while evaporation E and river runoff R deplete this store. The long-term water budget on land is:

$$P = E + R; \quad R = C. \qquad 1)$$

In the stationary case, export of liquid water from land to the ocean, R, is equal to net moisture import via the atmosphere C (here C is aerial moisture convergence) (Figure 39). For a given value of moisture import, evaporation from the forest cover increases rainfall (the so-called moisture recycling). For PNG mean rainfall is about $P = 3$ m year^{-1}, runoff is about $R = 2$ m year^{-1} and evaporation is consequently $E = 1$ m year^{-1}.

While the role of forests in moisture recycling via evaporation has long been known, recently new evidence was put forward indicating how forests are also responsible for the atmospheric moisture import: the crucial term in the terrestrial water budget. The biotic pump of atmospheric moisture was described, a mechanism by which natural forests can create and regulate ocean-to-land winds, bringing moisture to all terrestrial life (Makarieva and Gorshkov, 2007, 2010; Makarieva *et al.*, 2009; Sheil and Murdiyarso, 2009; Makarieva *et al.*, 2013c,a, 2014b; Nobre, 2014).

Physical bases of the biotic pump

What are the physical prerequisites for a non-zero net import of moisture to a certain area? Two conditions must be met: first, there must be an inflow of moist air towards the considered area. Second, this moist air must ascend over the area in question. If the air does not ascend but just passes over land in the horizontal direction, the moisture it contains will not precipitate but will be carried away with the air. Net import of moisture will be zero (as is always the net import of dry air).

Precipitation occurs in the rising air because of a peculiar property of the water vapor. Under terrestrial conditions water vapor is a condensable gas. It means that its concentration (the number of gaseous H_2O molecules per unit volume) cannot exceed a certain maximum value that is called the saturated concentration. Following the fundamental Clausius-Clapeyron law, the saturated concentration of water vapor grows exponentially with increasing air temperature. The water vapor concentration grows (or falls) by approximately twofold for each ten degrees of temperature rise (or fall).

Air temperature describes the mean kinetic energy of air molecules. When an air parcel ascends, its potential energy in the gravitational field of the Earth grows, but the kinetic energy of air molecules decreases. (A bouncing ball provides an analogy: as it rises, it loses kinetic energy and stops at the uppermost point of its trajectory, where its gravitational potential energy is at its maximum.) As the air temperature drops, the saturated concentration of water vapor in the rising air drops as well. At a certain point, where the temperature has fallen down to a threshold value (dewpoint), water vapor in the ascending air begins to condense. Condensation is accompanied by release of latent heat, which somewhat diminishes the rate at which air temperature further diminishes with height.

So how to ensure that, first, there is a horizontal inflow of air and, second, this air ascends over a given territory? It turns out that both conditions can be fulfilled if the air contains large amounts of water vapor. Winds tend to blow from areas of high air pressure to areas of low pressure. Air pressure at the planetary surface depends on the total number of gas molecules in the atmospheric column. When water vapor condenses, it disappears from the gas phase; the number of gas molecules diminishes, and the air pressure falls. Therefore, if the process of condensation is sustained over land, the latter becomes a persistent zone of low pressure.

Why should water vapor condense in a moist atmosphere? The reason is that moist air is not in a stable static equilibrium in the atmosphere of Earth. If a dry air parcel is occasionally displaced upwards in a static motionless atmosphere, air pressure in the parcel declines with height in such a manner that it is always equal to the weight of the gas in the atmospheric column above the parcel. Such distribution of air pressure is called hydrostatic. While air pressure is high at the surface and low in the upper atmosphere, this pressure difference does not make the air move. At any point the upward-directed pressure gradient force acting on the air parcel is precisely compensated by gravity. Therefore, no additional motion arises after an occasional displacement of a dry air parcel.

However, if a moist air parcel is occasionally displaced upwards, the situation is different. As water vapor condenses and leaves the gas phase, its partial pressure drops with height more rapidly than do the partial pressures of non-condensing air components with their mass conserved (Figure 40a). There appears an upward-directed uncompensated force that urges further ascent of moist air. Rapid restoration of hydrostatic equilibrium translates the non-equilibrium pressure gradient onto the horizontal plane, with the condensation area becoming the zone of low air pressure at the surface (Gorshkov *et al.*, 2012; Makarieva *et al.*, 2013c, 2014a). This condensation-driven air motion is distinct from the buoyancy-driven motions associated with latent heat release and would occur in the absence of latent heat release as well (i.e. if all latent heat is rapidly removed from the condensation area).

The larger the amount of water vapor in the atmospheric column, the greater the probability of the ascending air motion, rainfall and creation of the low pressure zone at the surface. With the total amount of moisture in the atmospheric column increasing from 40 to 60 mm the rainfall probability rises from 2.5% to nearly 20% (Figure 40b).

As life invaded land in the course of biological evolution, these physical laws were exploited by plants to switch on and regulate the water cycle on land thousands kilometers away from the ocean.

Biological and ecological bases of the biotic pump

Modern life is based on photosynthesis. Green leaves using the energy of solar photons to convert inorganic carbon of atmospheric carbon dioxide into organic compounds. To synthesize organic matter, the leaf must take CO_2 inside by opening the stomata – miscroscopic leaf pores. However, when the stomata open, water vapor from inside the leaf escapes to the atmosphere. Many more molecules of water vapor are emitted than CO_2 molecules let inside. On a global average, the ratio is 8 molecules assimilated CO_2 per one thousand molecules H_2O escaping from the leaf (Cramer *et al.*, 2009). This process of biotically-mediated emission of water vapor into the atmosphere is termed transpiration. Transpiration and evaporation of water from various surfaces constitute the total flux of water vapor from land to the atmosphere, where the plant-mediated contribution is dominant (Fisher *et al.*, 2009; Jasechko *et al.*, 2013). By opening and closing the stomata the plants can regulate the influx of water vapor into the atmosphere.

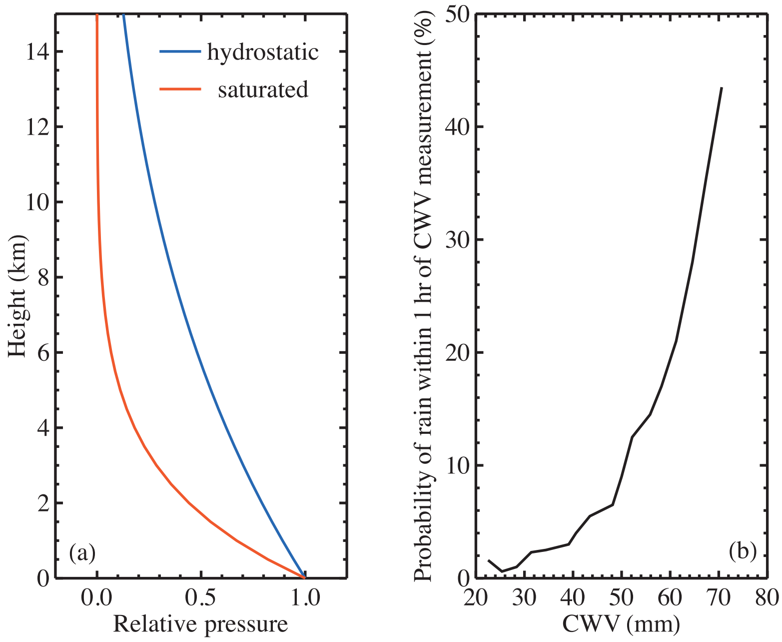


Figure 40. Biotic pump physical bases. (a) The dependence of relative saturated partial pressure of water vapor on height (red line) versus the hydrostatic air pressure (blue line) in a standard atmosphere with air temperature lapse rate 6.5 K km^{-1} (Makarieva and Gorshkov, 2007). The difference between the slopes of the two curves at any point quantifies the upward force associated with water vapor condensation. It is maximum in the low atmosphere and zero at the top of the troposphere. (b) The likelihood of rain as dependent on the amount of water vapor in the atmospheric column (CWV – columnar water vapor), data obtained by Holloway and Neelin (2010, their Fig. 10b) for an equatorial island. For equatorial rainforests CWV is around 50 mm (Makarieva *et al.*, 2014b).

The green foliage and branches of trees have a much greater cumulative area than the area of tree projection on the ground. The ratio between these areas, called leaf area index, is particularly high in equatorial rainforests and is estimated at about 5 for PNG (Buermann *et al.*, 2002, their Fig. 7). Hence, forest transpiration enriches the atmosphere with water vapor more efficiently than evaporation from an open water surface of the same area. Consequently, condensation occurs more readily over forests than over the ocean. Forests, rather than the ocean, become the low pressure zones to where the moist winds converge. Completing the cycle, moisture precipitates over the land and returns to the ocean in the form of river runoff.

Schematically, the biotic pump works as follows. Immediately after rain the local atmosphere is relatively dry (water vapor has condensed and precipitated). Winds are negligible. The atmosphere slowly regains water vapor via evaporation. Small differences in evaporation rates translate into large differences in the probability of rainfall due to the sharply rising relationship between water vapor content and the likelihood of rain (Figure 40b).

Thus rain is much more likely to start again over the forest, where instantaneous evaporation is higher, than over the ocean. Once sufficient water vapor has accumulated over the forest, condensation begins. Local air pressure starts to decline. In contrast to the gradual process of evaporation, condensation can occur very quickly. This is because the condensation rate is proportional to the vertical velocity of air, which can be arbitrarily high. The resulting pressure differences now draw wet air from the ocean to the forest, which then rises and cools. Now moisture generated locally via forest evaporation precipitates on land together with additional moisture brought from the ocean. This additional moisture is what ensures land remains wet while rivers keep running back to the ocean.

The biotic pump is a highly organized complex process. In order to sustain condensation that keeps the air pressure low on land – so that moist winds blow to land from the ocean – there must be intense evaporation from the forest canopy. But evaporation diminishes the amount of moisture in the soil. Moisture is additionally lost from the soil by runoff. If all the soil moisture is gone, evaporation stops, and so does the atmospheric moisture transport. This means that a non-trivial balance must be maintained: forest evaporation must be exactly such that it never fully depletes the soil moisture but at the same time is intense enough to ensure that the amount of moisture brought from the ocean by winds compensates moisture losses in the soil.

Native species that form natural forest communities have evolved a complex set of genetically encoded biophysical and morphological traits that make the biotic pump possible. These traits took hundred million of years to evolve and are different in different regions of the world. The need to keep evaporation high for running a rich water cycle explains one of the long-standing biochemical puzzles – why plants appear to be "wasteful" of water during photosynthesis. The apparently low water use efficiency of plants has been traditionally interpreted as an "unavoidable evil", "land plants dilemma" etc. This implies that biological evolution was unable to produce a more efficient biosynthesis process that would use water more sparingly (Cramer *et al.*, 2009). However, there are many plants, especially in the arid environments, that have a much better water use efficiency than the global average, so the evolutionary explanation ("bad luck") is apparently not valid. The biotic pump explains that plants benefit from spending more water vapor as moisture returns to them with surplus owing to the moisture convergence initiated in a moist atmosphere by high evaporation (Figure 39). The biotic pump is a clever *investment* of moisture: the forest must spend it wisely to gain more in return than it has spent.

Another very important property of forest ecosystems is their ability to regulate cloud formation. At one and the same temperature, condensation commences at a higher concentration of water vapor in a very clean atmosphere than it does in an atmosphere containing small particles – aerosols. Such particles called cloud condensation nuclei serve as centers for condensation by providing a surface where water vapor molecules could meet and form intramolecular bonds to become liquid. By emitting the necessary biochemical compounds in the right amounts forests can switch on condensation even if the water vapor concentration above the forest is relatively low. Recent studies reveal the high diversity of biogenic aerosols and the complex chemistry behind their transformations in the atmosphere (Park *et al.*, 2013; Riccobono *et al.*, 2014). It was established that these compounds are not just biochemical products of tree functioning, but, rather appear as a product of the ecosystem as a whole including complex interactions between autotrophs (plants) and heterotrophs (bacteria, fungi) (Pöhlker *et al.*, 2012; DeLeon-Rodriguez *et al.*, 2013; Morris *et al.*, 2014).

To name other important biological and ecological components of the biotic pump: the root system of forest trees facilitates both storage and extraction of moisture from soil (Asbjornsen *et al.*, 2011); the large height of trees determines the vertical temperature gradient under the canopy, keeping soil evaporation under biotic control (Makarieva *et al.*, 2006); tall trees are also essential for surface roughness that prevents extremely high wind velocities from developing (Pielke *et al.*, 1998). Thus, natural forests not only create an ocean-to-land moist air flow, but also stabilize this flow at an optimum level and prevent its extreme fluctuations like hurricanes, tornadoes, severe droughts or floods. Species other than plants (bacteria, fungi, animals) are essential for the stability of the forest ecosystem itself ensuring an efficient and stable cycling of all life important elements.

Information processing capacity of natural forests

One may ask whether it is possible to replicate the biotic control of water cycle by technological means. As discussed above, the biotic pump is a complex process of environmental assessment and corresponding reactions of the totality of organisms composing the forest ecosystem. For example, root cells monitor the amount of moisture in soil and send biochemical signals to leaves as to whether the stomata should be opened or closed (Davies and Zhang, 1991; Henson *et al.*, 1989; Huc *et al.*, 1994). These processes are based on genetic information of the biological species composing the forest ecosystem. The energetic basis for such a control is solar radiation absorbed by plants. The global mean efficiency of solar energy transformation by plants into the energy of organic carbon which powers all living organisms is about 0.5%. Net productivity of tropical forests is about 10 Mg C ha^{-1} $year^{-1}$ (Hertel *et al.*, 2009; Ghazoul and Sheil, 2010), which is equivalent to 1.3 W m^{-2} for organic carbon energy content of 42 kJ $(gC)^{-1}$. The flux of absorbed solar radiation at the surface in the tropics is about 200 W m^{-2} (Hatzianastassiou *et al.*, 2005). This gives an efficiency of photosynthesis of 0.65%. Rainforests on the Maritime Continent can be exceptionally productive up to about 20 Mg C ha^{-1} $year^{-1}$ (Hertel *et al.*, 2009), which implies an energy efficiency of over 1%.

Energy from the Sun arrives on Earth in the form of short-wave photons (Figure 41). On Earth this energy transforms into the chaotic energy of thermal photons that are emitted back to space. Photon's energy is proportional to kT, where $k = 1.4\times10^{-23}$ J K^{-1} is Boltzmann constant, T is the absolute temperature of radiation. The mean energy of solar and thermal photons is determined by temperatures of the Sun and the Earth, respectively, $T_S \sim 6000$ K and $T_E \sim 300$ K. The energy of solar photon as it dissipates into thermal photons is conserved. From the equality $kT_S = nkT_E$ we find n = 20: each solar photon decays on Earth into about twenty thermal photons. This decay can go through different channels. The unbounded diversity of possible decay channels maintains all ordered processes on Earth, both in animate and inanimate nature. If the Sun were sending to the Earth the same flux of energy but in the form of thermal photons that are emitted by the Earth, the temperature of the Earth's surface could be about the same as it is now. But the decay of these thermal photons would be impossible. All the decay channels were closed. The Earth would remain warm, but no ordered processes would occur on its surface. Life could not exist (Figure 41).

The main difference between life and inanimate nature pertains to the fact that life uses decay channels that are by many orders of magnitude more complex than in the non-living world. Orderliness of biological systems is characterized by molecular (not macroscopic as in the inanimate nature) "memory cells" or degrees of freedom. Per each square micron of the Earth's surface there are several independently functioning living cells - plankton in the ocean, bacteria, fungi and plants on land. These cells monitor the environment and react to its local changes in a non-random way.

For example, with increasing ambient concentration of CO_2 rainforest trees are able to decrease stomatal conductance and thus improve water use efficiency (the amount of water vapor released by transpiration per mol carbon dioxide fixed in primary productivity). Loader *et al.* (2011) found that large trees in a pristine rainforest in Borneo behave in this manner. Improved water use efficiency can allow the forest ecosystems to increase productivity at constant rainfall thus absorbing extra carbon from the atmosphere and compensating for the accumulation of anthropogenic carbon in the atmosphere.

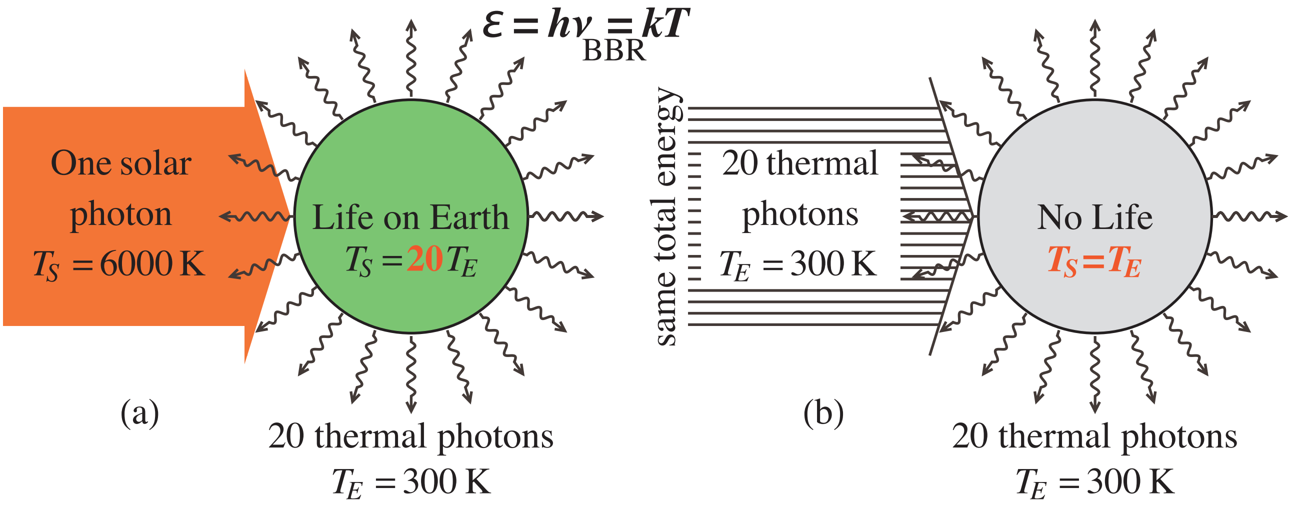


Figure 41. Solar energy transformation on Earth. Radiation consists of particles – photons. Photon energy is $\varepsilon = h\nu = kT$ for blackbody radiation (BBR) of temperature T. Radiation power is $J = n\varepsilon$ (n is the number of photons radiated per unit time). (a) Earth receives power $J_S = 1.4\times10^{17}$ W of solar radiation with $T_S \approx 6000$ K and emits power J_E of thermal radiation with $T_E \approx 300$ K. Energy on Earth does not accumulate (steady state): $J_E = J_S$, so $n_E/n_S = \varepsilon_S/\varepsilon_E = T_S/T_E = 20$. Each solar photon decays on Earth into 20 thermal photons. Any events on Earth are possible because Earth's temperature is 20 times less than Sun's. (b) If those temperatures coincided, Earth would have been almost completely "uneventful", existing in a state close to thermodynamic chaos. Life on Earth would be impossible even if the Earth remained as warm as it is now.

Living cells exchange energy, matter and information with the environment as prescribed by their genetic program coded in the DNA molecules. The rate of information exchange between living cells and their environment can be estimated from the known rate of their energy consumption. Absorption of one solar photon by a plant cell changes the state of about twenty molecular memory cells within the cell as the solar photon decays into thermal photons. Assuming that one molecule corresponds to one memory cell with two possible states - excited (after absorption of energy of the order of kT_E) and non-excited (after release of this energy) - we obtain that one act of excitation and relaxation corresponds to a flux of information of one bit per act. With the global mean efficiency of photosynthesis of about $\varepsilon = 0.5\%$ and the global mean flux of solar energy absorbed by the planetary surface of about $F = 170$ W m^{-2}, the global flux I of information processed by living cells on the Earth's surface of area $S_E = 5\times10^{14}$ m^2 is estimated as $I = \varepsilon F S_E/(kT_E) = 10^{35}$ bit s^{-1} (Gorshkov *et al.*, 2000; Makarieva *et al.*, 2014c).

Figure 42. Technological and ecological information processing systems. Left panel: Tianhe-2, world's fastest supercomputer located in China (photo Jack Dongarra). Tianhe-2 performs 34×10^{15} operations per second, occupies 720 m^2 and consumes 24×10^6 watts. The supercomputer information processing rate per unit area is 5×10^{13} operations per second per square meter and energy consumption is 3×10^4 watts per square meter. Right panel: Rainforest in Papua New Guinea (photo Rocky Roe & UPNG Remote Sensing Centre) has a rate of information processing 2×10^{20} operations per second per square meter, which is over a million times faster than Tianhe-2. The rainforest energy consumption is 200 watts per square meter, i.e. it is over a hundred times more efficient than Tianhe-2. The energy efficiency achieved by life is unprecedented. An egg transforms to a chicken without any external energy consumption. Internal energy losses (heat dissipation) during embryonic development in some reptilian and insects do not exceed 10% of the initial energy store of the egg. The egg-to-chicken transformation represents an irreversible process of decay that is characterized by a diversity of channels that is unimaginable in our civilization.

There is virtually a precipice between the information processing capacities of the biosphere and computer technologies of our modern civilization. It pertains to total fluxes of information as well as the energy efficiency of information processing. If all people on Earth had a modern PC that runs about 10^{11} operations per second, the total flux of information processing by the humanity would not exceed 10^{21} operations per second. This is 14 orders of magnitude less than in the biosphere. Real rates of information processing in our civilization are much lower. For example, GOOGLE search processes data at rate of about 10^{13} bit s^{-1}, i.e. by 22 orders of magnitude more slowly than the biosphere. Modern supercomputers are able to perform about 10^{16} operations per second. They occupy an area of about 10^2 m^2 and consume power of about 10^7 W. Their energy expenditure per operation - about 10^{-9} J per operation - is twelve orders of magnitude larger than in the biosphere ($kT_E \approx 4\times10^{-21}$ J). If the entire Earth's surface had been covered with such supercomputers, their total flux of information processing would have been 5×10^{28} bit s^{-1}. This flux is two million times a smaller than is currently processed by the biosphere. Meanwhile the energy consumption rate of such a global computer network would have been five hundred times larger than the flux of solar energy at the surface, a hundred thousand (10^5) times larger than the energy consumption of the biosphere and one million times larger than the energy consumption of modern civilization (Figure 42).

Most importantly, unlike civilization, the natural forest as a community of species has a genetic program of environmental regulation. This program is directly coupled to the environment via the biochemical and biophysical energy and matter exchange. It is not possible to create a technological analogue of the biotic pump. Monocultures or plantations representing a random set of plant species do not possess the required set of correlated traits (it is an incomplete program or a broken algorithm). To give two extremely simplified examples: if one plants cacti, they will evaporate too little and will be unable to keep the atmosphere persistently moist. If one plants eucalyptus, they will evaporate readily but will be unable to prevent soil from drying. In either case, the biotic pump will not work.

Forests and atmospheric circulation in PNG

Major circulation cells

We have so far discussed how natural forest is a powerful solar-powered bioreactor with a complex program that efficiently controls precipitation via energy and matter exchange with the atmosphere. To understand the role such a bioreactor residing on the Maritime Continent can play in the regional and global climates it is necessary to have in mind the major air circulation patterns that connect the various parts of the planet (Figure 43). The general atmospheric circulation on Earth consists of three meridional circulation cells in each hemisphere. There are two so-called Hadley cells that occupy the regions from approximately 30 degrees latitudes to the equator. Within these cells the sea level air pressure falls towards the equator. Hadley cells border with the so-called Ferrel cells where the direction of the pressure gradient is reversed: pressure now falls from a maximum located around 30 degrees towards a minimum around 60-70 degrees latitudes. Finally, there are two polar cells where surface air pressure falls from the poles towards the Ferrel cells. At the surface these pressure gradients cause meridional winds to blow from the pressure maxima towards the pressure minima: thus, winds blow towards the equator in Hadley cells, and towards the 60th latitudes in Ferrel and polar cells.Owing to the fact that our planet rotates around its axis, the meridional pressure gradients also bring about zonal air winds (air motion along the parallels). In Hadley and polar cells the predominant direction of the zonal winds is from east to west, while in Ferrel cells it is the reverse because of the reverse direction of the pressure gradient (Figure 43).

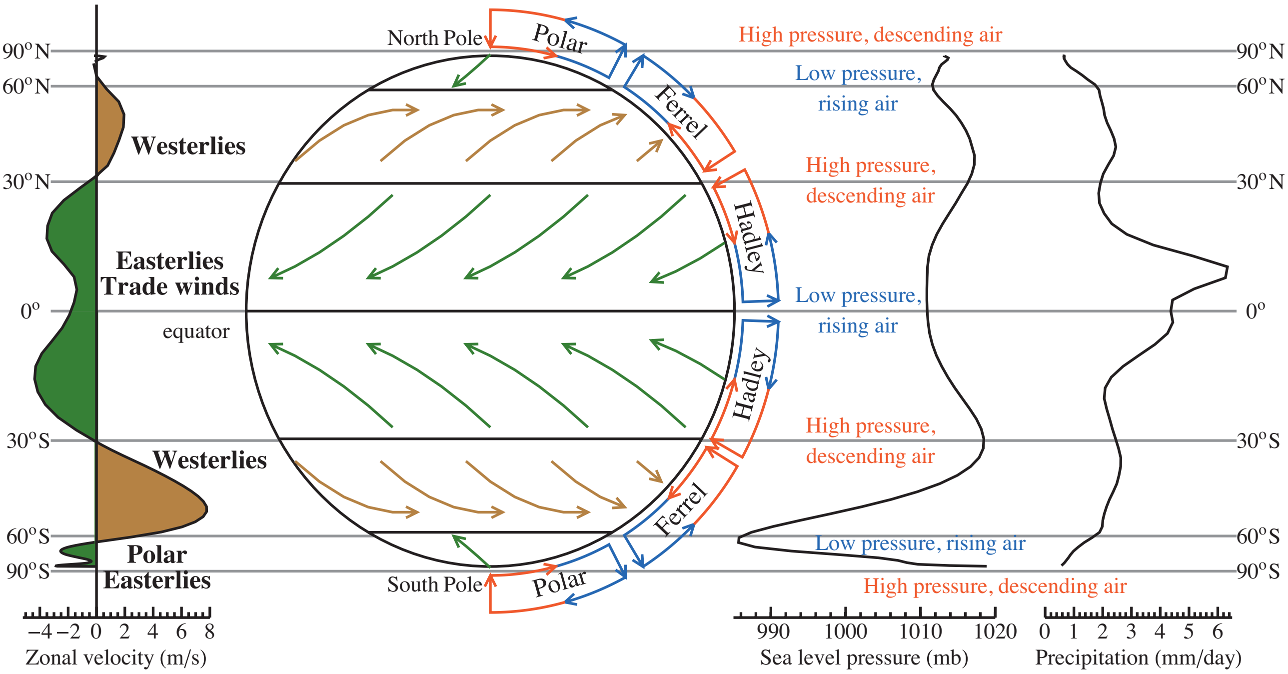


Figure 43. General circulation on Earth. The central scheme shows the axisymmetric circulation cells. Also shown are the zonally averaged annual mean zonal velocity, sea level pressure and precipitation as dependent on latitude. Note the lack of symmetry between the two hemispheres. Data source: monthly data from NCAR-NCEP reanalysis averaged for 1978-2013 (Kalnay *et al.*, 1996).

The zonal wind can be easily understood from considering the balance of forces acting on a rotating object. Consider an air parcel that is motionless relative to the rotating Earth. The centrifugal force that is proportional to squared velocity of rotation and inversely proportional to radius pushes the air away from the axis of Earth's rotation. But the centrifugal force is balanced by the centripetal force (vector sum of gravity, friction and the vertical pressure gradient) that pulls the air in the reverse direction – inward, towards the rotation axis. If we now impose a pressure gradient like in a Hadley cell (Figure 43), this gradient pulling the air towards the equator will also push the air away from the Earth's rotation axis (since the distance to the axis at the equator is maximum.) Thus, this gradient will contribute to the action of the centrifugal force. Since the opposite centripetal force has not changed, for the balance to be maintained the centrifugal force acting on the air must decrease, i.e. the air rotation must slow down. As our planet rotates from west to east the air rotation is slowed down when the air acquires an easterly velocity (i.e. when it moves from east to west in the opposite direction to the planet's rotation). Thus, the Hadley pressure gradient causes the tropical easterlies (Figure 43). (These effects can be described by introducing a formal Coriolis force.)

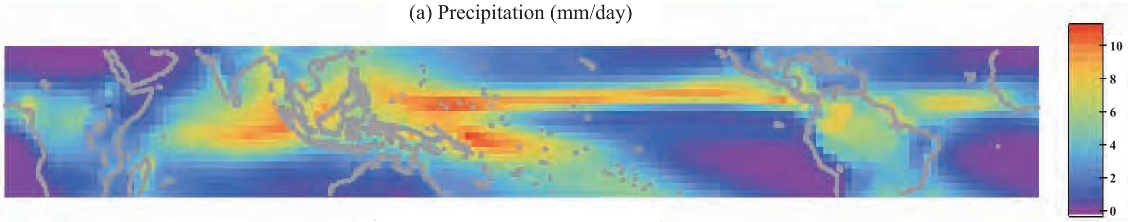
If the Earth were completely covered by the ocean, circulation cells in the two hemispheres would have been symmetric. In reality the three cells (Hadley, Ferrel and Polar) are most pronounced in the Southern Hemisphere (Figure 43). In the Northern hemisphere where most land is situated only the Hadley cell is well pronounced. In the temperate and high latitudes the meridional pressure gradients, as well as meridional and zonal winds, are small and may sometimes have opposite directions compared to the major circulation cells.

As the low-level air converges towards the equator, it rises. Then it returns back towards the higher latitudes in the upper atmosphere. As moist air rises, it cools and the water vapor contained in the low-level air, condenses and precipitates. The low-level air convergence is the cause of the precipitation peak observed in the vicinity of the equator. The axisymmetric circulation cells co-exist with zonally asymmetric circulation cells. They are manifested as precipitation maxima that are located around the Amazon forest, equatorial Congo forest and the Maritime Continent (Figure 44a). For the Maritime Continent the most important zonal cell is the Pacific Walker circulation. .

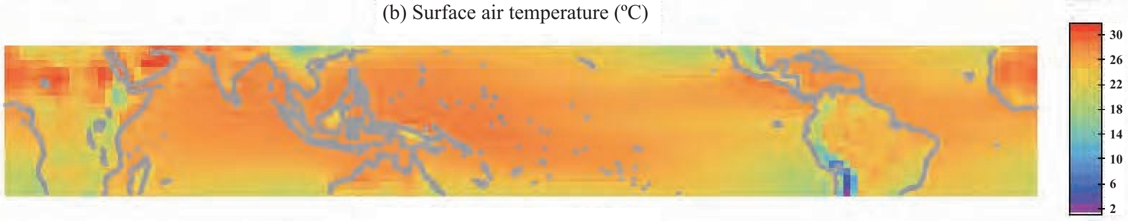
Walker circulation

Walker circulation is a zonal circulation cell with the low-level air moving from the high pressure region of the eastern Pacific ocean towards the low pressure zone over the Maritime Continent (Figure 45). The atmospheric air motion is coupled to oceanic circulation. As the surface winds blow from east to west, the wind stress causes a significant rise of the sea level around the Maritime Continent compared to the eastern Pacific. Sea level height around PNG is about 0.5 m higher than at the Peru coast at the same latitude. Since the westward wind stress acting on tropical waters tend to slow down their rotation (compared to that of the Earth's), the balance between the centrifugal and centripetal forces is broken in favor of the latter. Under the action of the now uncompensated centripetal force the surface the equatorial waters begin approaching the Earth's axis, which means that they flow poleward away from the equator. To maintain the mass balance and replenish the equatorial waters there appears an ascending motion of cold waters at the equator (the effect is known as Eckman pumping). These cold waters work to keep sea surface temperatures significantly colder in the eastern Pacific than they are around the Maritime continent (Figure 44b).

(a) Precipitation (mm/day)



(b) Surface air temperature (ºC)



(c) Sea level pressure (hPa)

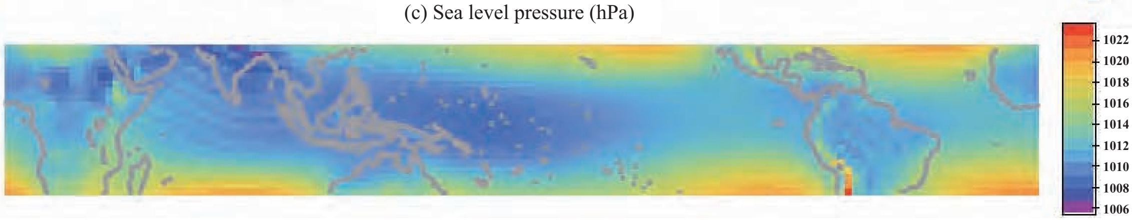


Figure 44. Spatial distribution of (a) annual mean precipitation, (b) annual mean temperature and (c) annual mean air pressure at the sea level in the tropics. Data source: monthly data from NCAR-NCEP reanalysis averaged for 1978-2013 (Kalnay *et al.*, 1996).

If the zonal winds weaken, the oceanic currents, including the upwelling at Peru coast, weaken as well. The east and central Pacific warm, such that the temperature gradient is reduced. If additionally the condensation zone moves to the east, an El Niño sets in. When the Walker circulation is strong, a La Niña gets established. These phenomena are well-known for their long-distance impacts on the climate of the Americas as well as even more distant global regions (Philander, 1990).

However, a theoretical explanation for the location and intensity of the Walker circulation remains elusive. It remains unclear why the condensation maxima are located where they are and what controls the switch between the El Niño and La Niña conditions. Zonal sea surface temperature gradients are often considered as the cause of the Walker circulation.

As the landmasses warm faster than the ocean it is thought that enhanced rainfall is related to the location of the landmasses (Figure 44a). The warm land surfaces become the zones of low pressure that favors convection and rainfall. Simplified, the rationale is as follows. The colder the air, the more rapidly its pressure drops with increasing altitude. Thus in the warmer regions the air pressure is higher than it is in the colder regions in the upper atmosphere (somewhere around the height of the jet flights). This pressure surplus causes air to diverge (pushes the air away) from the warmer region. Since surface air pressure reflects the weight of air in the atmospheric column, as the amount of air in the warmer region diminishes, so does the surface pressure. In the result, an area of lower pressure forms where the surface is warm Figure 45.

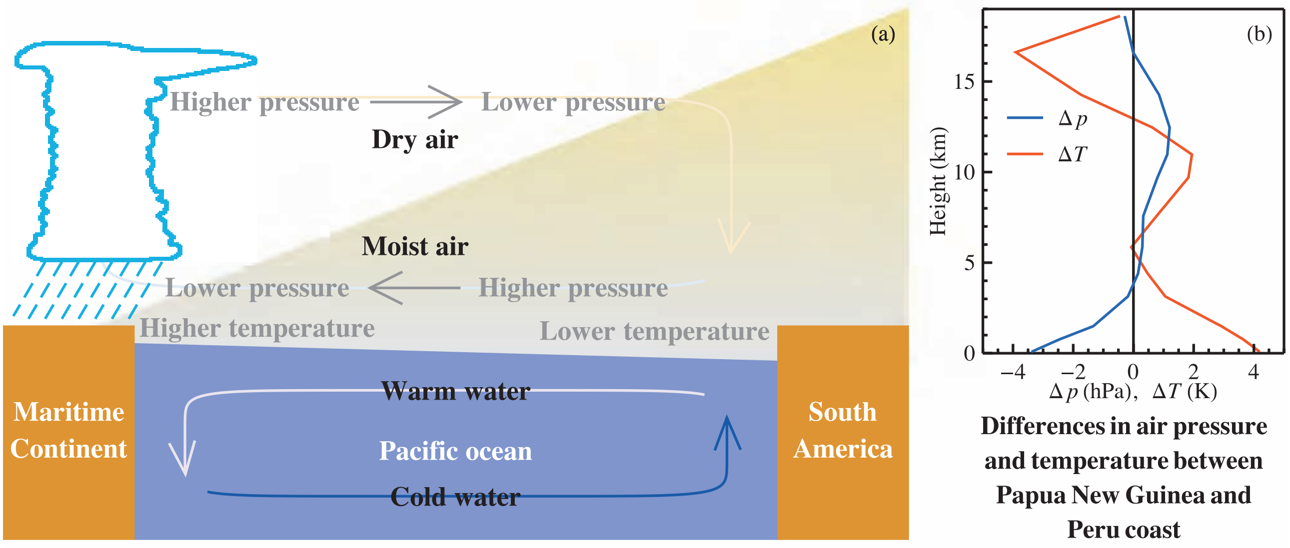


Figure 45. Walker circulation in the tropical Pacific Ocean. (a) Scheme of the zonal air and water motions and horizontal temperature and pressure differences. (b) Vertical profile of the annual mean differences in air pressure and air temperature between the western and eastern borders of the Walker circulation. Air pressure and temperature profiles were calculated for PNG (−10°S - 0°S, 140°E - 150 °E) and the coastal region of Peru (−10°S - 0°S, 265°E - 275 °E) using the monthly data from NCAR-NCEP reanalysis averaged for 1978-2013 (Kalnay *et al.*, 1996).

Apart from general theoretical difficulties considered below, in relation to the Walker circulation this explanation is not satisfactory. First, land surfaces in the areas of maximum precipitation are cooler than the neighboring ocean (Figure 44b). Second, it was gained from observations that while the development of El Niño conditions is usually accompanied by a weaker zonal temperature gradient, such weakening does not always precede El Niño events. For example, the development of El Niño of 1982-1983 notable by its large amplitude was not preceded by any anomalously warm conditions in the eastern Pacific (Philander, 1990). Nor is such eastern Pacific warming necessarily followed by an El Niño.

It was appreciated quite early that rather than surface temperature gradients, it is the location of the condensation zone itself that dictates the intensity of the Walker circulation (Cornejo-Garrido and Stone, 1977; Philander, 1990). The physical mechanism is thought to be similar: the release of latent heat in the troposphere diminishes the rate at which air temperature declines with height. Thus the atmosphere where condensation occurs should be on average warmer than where condensation is absent (Figure 45b). This mean tropospheric temperature contrast, similar to the surface temperature contrast, translates into an upper-level pressure contrast, which should push the air in the upper troposphere away from the condensation area. However, in this logic it is unclear why condensation should be anchored to land like the Maritime Continent. The recurrence of El Niños demonstrate that a different state of the climate system is possible with the rainfall maximum moving away from the Maritime Continent. Generally, understanding the physical link between the phase transitions of water and air circulation dynamics is recognized as a major and persistent challenge for climate science (Stevens and Bony, 2013).

Forest climate impact and challenges in the atmospheric science

Indeed, one of the major challenges faced by the climate science is that it cannot confidently predict patterns of atmospherics dynamics that are associated with water vapor condensation. This results in poor predictions of the intensity of tropical storms, monsoons as well as long-term forecasts of precipitation changes in the warming climate. Current incomplete understanding of the physical principles governing low-level circulation is manifested by the inability of atmospheric models to replicate the terrestrial water cycle (Marengo, 2006; Hagemann *et al.*, 2011) as well as by the challenge of confidently predicting precipitation and air circulation (e.g., An, 2011; Acharya *et al.*, 2011; Huang *et al.*, 2013). Since forests are major players in the atmospheric moisture cycle, models that lack an adequate representation of condensation dynamics cannot confidently estimate the climatic impacts of deforestation.

For humans the most important winds are those blowing near the Earth's surface. Namely these winds carry moisture from oceans to land and determine our life. As with the Walker circulation, the main driver of winds is considered to be differential heating, either in the troposphere due to latent heat release or at the surface due to land-sea contrasts or solar irradiance gradients. Temperature gradients generated by differential heating create pressure gradients in the middle to upper troposphere. However, while the pressure surplus in the upper atmosphere in the warmer regions can be directly calculated from the temperature difference between the warmer and the colder regions, the pressure shortage at the surface is of secondary origin. It is not directly related to temperature, but depends on the dynamic air re-distribution between the warmer and the colder regions. Therefore, the magnitude of pressure gradients at the surface cannot be deduced from the tropospheric pressure gradients related to differential heating. The speed and direction of the low level winds cannot be quantified from temperature gradients either.

The second problem pertains to the determination of the low-level circulation itself. Even if we know the magnitude of the pressure gradient at the surface, this does not help much for the determination of the low-level circulation. Low surface pressure may exist without any appreciable air convergence and hence without any precipitation. In this case area with low surface pressure becomes the center of slow air rotation, whereby the air moves largely parallel to the isobars (curves of equal pressure) rather than converges across the isobars from the higher to the lower pressure. And when the air does not converge, it does not rise and there is no rain.

These theoretical challenges are of utmost practical importance for the people of Papua New Guinea as they pertain to the question how rainfall and temperature regime might change if the forest cover is disturbed beyond a threshold. Forests, as are a significant store and source of moisture on the Maritime Continent, ensure a continuous evaporation flux, keep the atmosphere moist and thus ensure that condensation occurs with high intensity over the Maritime Continent. Forest-induced condensation not only impacts the lapse rate via latent heat release in the atmosphere but it also creates low-level pressure gradients directly by removing water vapor from the atmospheric column (Makarieva and Gorshkov, 2007; Makarieva *et al.*, 2009, 2013a). These pressure gradients are proportional to condensation rate and the vertical air velocity. As such, they are associated with cross-isobar air motion and are directly relevant for the estimate of wind power. From the biotic pump theory it follows that global circulation power is proportional to the global precipitation rate, which is in good agreement with observations (Gorshkov *et al.*, 2012; Makarieva *et al.*, 2013c,b).

The importance of meteorological studies in PNG

One of the important theoretical questions is how condensation influences surface pressure. Generally in the tropics low surface pressure is spatially associated with high surface temperature. This can be explained considering the so-called isobaric height – a certain pressure level with its altitude remaining constant despite changing surface temperature and pressure. If such a level exists, in areas where temperature is high and air density is low there will be less air below the isobaric height than where temperature is low and air density is high. Accordingly, surface pressure equal to the weight of the air column will be lower in the warmer than in the colder areas. It is conventionally presumed that air will converge to the zone of high temperature.

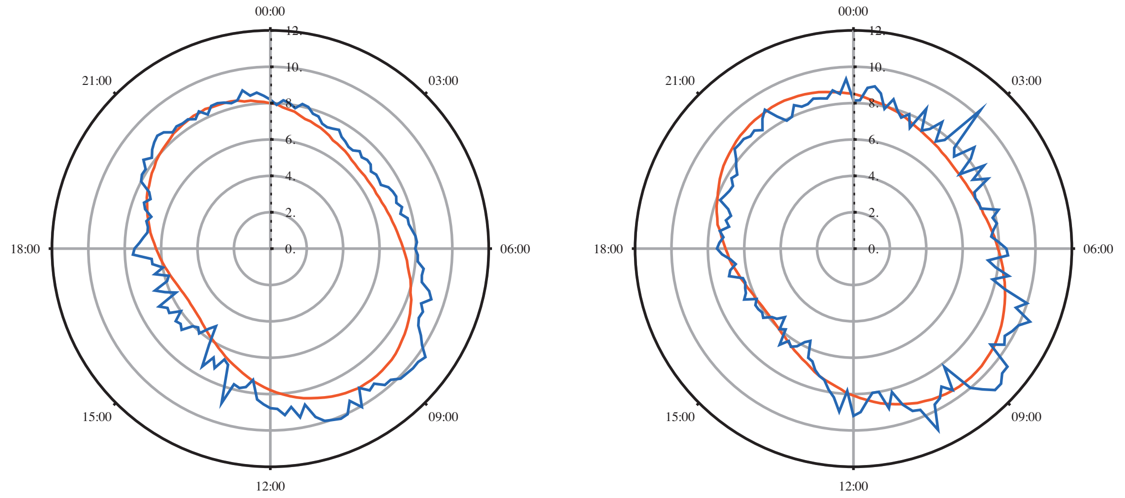
However, the attempts to explain recent acceleration of the Walker circulation on the basis of an increased temperature difference between the Indian and east Pacific Ocean were not successful (Han *et al.*, 2014; McGregor *et al.*, 2014). Models predicted the largest acceleration of winds west of 150°E, while in reality winds in this region did not change at all or even slightly reversed (Han *et al.*, 2014; de Boisséson *et al.*, 2014). Moreover, convergence and ascent of moist air in the tropics with cloud formation can lead to a decrease of temperature rather than increase it. Dry land areas under abundant sunlight may have much higher temperatures than the ocean but do not become centers of moist air convergence. In the view of these uncertainties modern models do not agree even on the basic mechanisms of how regional precipitation will change in a warming climate. Some models predict that the warmer areas will get wetter, while others predict that the wet areas will get wetter (e.g., An, 2011).

It is therefore necessary to quantify the impact of condensation on surface pressure and to compare air pressure dynamics in moist forested and drier deforested land regions. This would help to assess and understand the large-scale dynamics of the Walker circulation and precipitation patterns over the Maritime Continent and especially in PNG, which is a global hotspot of condensation and rainfall. However, recent meteorological information from PNG has been very scanty. In recent years PNG represents a relatively empty area on the global maps of meteorological stations (e.g., Matsuura and Willmott, 2015; Yatagai *et al.*, 2012)[1]. But recently an extensive network comprising 37 automatic meteostations was established in PNG by the University of PNG Remote Sensing Center (www.pngclimate.net). The stations provide 10-minute records of rainfall, temperature, solar radiation, air pressure, wind velocity and direction. Such high resolution data are of great value in investigating moisture dynamics.

Despite the relatively short record, data from these stations already provides intriguing evidence concerning the relationship between air pressure and rainfall. It was established recently that rainfall in the Amazon rainforest is associated with a slightly higher daily pressure than rainfall in drier unforested regions where during rainy days the air pressure falls (Makarieva *et al.*, 2014b). It was suggested that the difference could be explained by higher moisture amounts in the atmospheric column during rainy days, however, the effect was not strong enough to fully account for the observed difference. Analysis of the rainfall data for 2012-2013 collected on the meteorological stations of UPNG Remote Sensing Centre confirm that on a much shorter temporal scale rainy hours are on average characterized by higher pressure than rainless hours, although the magnitude of the difference varies from station to station and from hour to hour (Figure 46a,c). The data also show that rainy hours are usually characterized by lower temperature than rainless hours (Figure 46b,d).

(a) Kerema: pressure

(c) Port Moresby: pressure



(b) Kerema: temperature

(d) Port Moresby: temperature

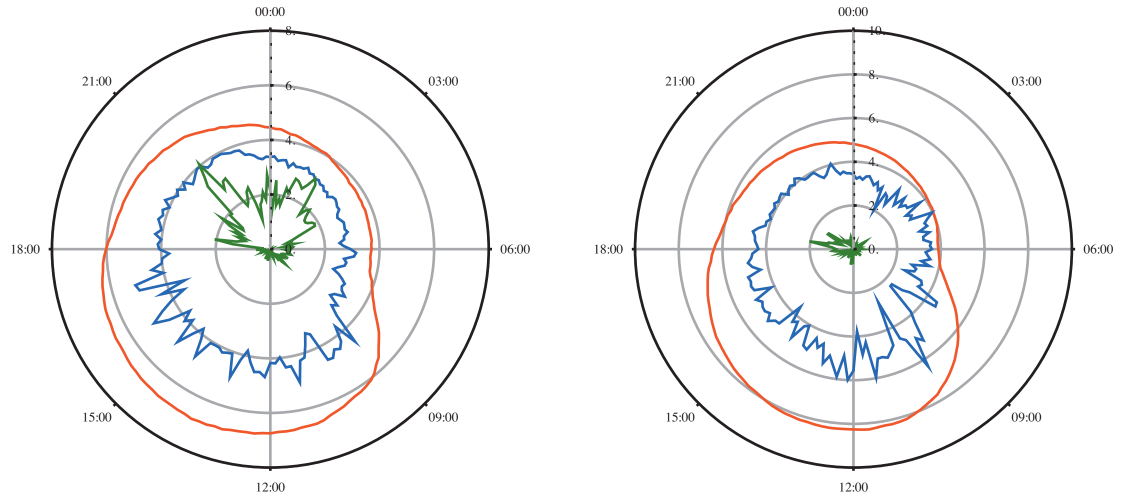


Figure 46. **Diurnal cycle of pressure (a, c) and temperature (b, d) for rainy (blue curve) and rainless (red curve) 10-min periods in (a, b) in 2013 in Kerema (station no. 7, 7.99°S, 145.79°E, 148 m a.s.l., annual rainfall 10.5 mm/day) and (c, d) in 2012 in Port Moresby (station no. 1, 9.41°S, 147.16°E, annual rainfall 3.5 mm/day). Pressure (in hPa) and temperature (in degrees Celsius) is shown with the minimum value recorded during the year of observations subtracted (984.9 hPa and 20.7°C for Kerema, 985 hPa and 19.7°C for Port Moresby). The green curve in (b, d) shows the diurnal cycle of rainfall in cm/day. The red (rainless) curves are smoother than the blue (rainy) ones because of a much larger number of rainless 10-min periods. Note the pressure minima at around 15:00 and 03:00 in (a, c).**

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[1] See http://climate.geog.udel.edu/~climate/html_pages/Global2014/ (precipitation station locations) and http://www.chikyu.ac.jp/precip/products/index.html

To quantify the dependence between pressure and temperature for each station mean pressure and mean temperature were was calculated during each hour using all 10-min observations for that hour obtained during the year (a total of 6x24x365=52,560 measurements for each station). Then, separately for rainy and rainless periods, mean pressure and temperature were calculated for, respectively, the 50% lowest and the 50% highest pressure values. The ratio between pressure Δp and temperature ΔT differences was used as a quantitative measure of the dependence between pressure and temperature. For example, at Kerema station at 12:00 the lowest and the highest 50% pressure values during rainless 10-min periods differ by −1.8 hPa, while the mean temperatures for the same two sets of observations differ by +2.5 K (i.e. lower pressure is associated with higher temperature). This corresponds to $\Delta p_d/\Delta T_d$ ratio of −0.7 hPa K^{-1} at 12:00 at Kerema station. Here subscript d stands for "dry" (rainless 10-min periods). A similar ratio calculated for the rainy periods is $\Delta p_w/\Delta T_w = -0.4$ hPa K^{-1} (*w* for "wet").

The mean ratios calculated for 24 hours for 19 stations with a complete annual record in 2012 or 2013 are similar for rainless and rainy periods and constitute −0.5±0.4 and 0.6±0.4 hPa K^{-1} for rainless and rainy periods, respectively (± standard deviation, $n = 456$). This information helps to disentangle the impact on surface pressure of surface temperature and rainfall. For each hour for each station studied, an expected pressure during rainy periods was calculated using the established $\Delta p_d/\Delta T_d$ ratio and the difference between mean temperatures during rainy and rainless periods, respectively (cf. Figure 46b, d).

This expected pressure was compared with the actual pressure during rainy periods. Their difference plotted for each hour for 19 stations in Figure 47a shows that rainy periods have significantly *lower* pressure than could be expected from their temperature. This pressure shortage, which on average constitutes 0.5 hPa, depends on the time of the day and appears to be correlated with rainfall intensity (Figure 47b) (the mean amount of rain during rainy 10-min periods). It reaches a maximum at around 3 p.m.

If the vertical structure of the atmosphere is constant (in particular, the isobaric height does not change), temporal changes between relative pressure and temperature reflect the corresponding spatial differences. The obtained relationship means that for one and the same temperature surplus, other conditions being the same, the decrease of surface pressure will be higher when the rainfall is higher, with the difference positively related to rainfall intensity. This pattern is qualitatively consistent with observations. Figure 48 compares the vertical profiles of air pressure and temperature between a relatively dry near-equatorial region (Horn of Africa) and PNG. The figure shows that PNG with its higher rainfall displays a significantly lower sea level pressure than the much drier Horn of Africa.

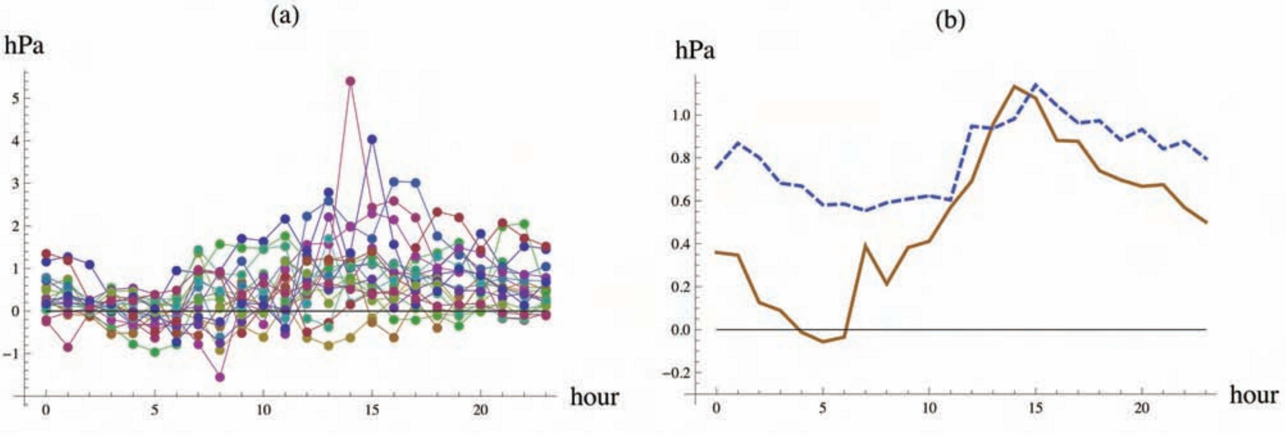


Figure 47. The expected pressure shortage (hPa) due to condensation calculated as $\delta p \equiv (T_w - T_d) \times \Delta p_d/\Delta T_d - (p_d - p_w)$. Here T_w, p_w, T_d and p_d are the mean temperature and pressure during rainy (*w*) and rainless (*d*) 10-min periods, $\Delta p_d/\Delta T_d$ is the coefficient describing the relationship between pressure and temperature during rainless periods (see text). A positive δp means that "rainy" pressure increases less with declining temperature (or decreases more with increasing temperature) than one could expect from the temperature-pressure dependence established separately for rainless periods. (a) δp values for different time of the day for 19 stations of the UPNG Remote Sensing Center which have a complete record for 2012 or 2013. (b) The mean δp from (a) (solid brown curve) and the mean precipitation intensity in mm (10 min)−1 (dashed blue curve) for the same stations. Precipitation intensity is the mean rainfall amount during rainy 10-min periods.

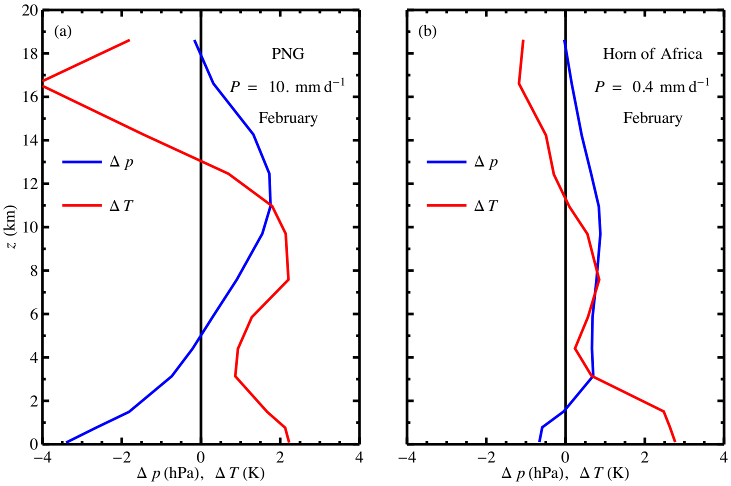


Figure 48. Vertical profiles of air pressure and temperature differences between the zonal mean (25°S - 25°N) in February and (a) Papua New Guinea mainland (−10°S - 0°S, 140°E - 150 °E) and (b) Horn of Africa (0°N - 10°N, 40°E - 50°E). *P* is precipitation in February in these regions.

The established dependence between the relative pressure shortage due to condensation and rainfall rate can allow one to estimate changes in air pressure from the known rates in rainfall. More theoretical and observational studies are needed to validate the obtained relationships across diverse datasets and regions of the worlds. If confirmed, such relationships will provide a clue to some of the major challenges of atmospheric science: the interplay between condensation and air circulation. It would also be a key for evaluating the biotic pump intensity on a regional scale and will inform predictions of the possible effects of deforestation across the world.

Climatic consequences of deforestation for the water cycle in PNG

The biotic pump of atmospheric moisture draws moisture to land from the ocean. Moisture import occurs on a smaller scale via the interaction with the adjacent ocean at a scale comparable to the size of the Maritime Continent itself. It also occurs on a larger scale with moisture coming from the eastern Pacific as well as from the higher tropical latitudes in conjunction with the Walker and Hadley circulations, respectively. Deforestation of the Maritime Continent and especially in PNG, where the rainfall reaches its local maximum (Figure 44a), can affect both components of the moisture transport via displacement of condensation maxima. The biotic pump also impacts the stability of the water cycle. Deforestation threatens with a more chaotic rainfall and more frequent droughts and floods. Below we discuss the various scenarios as well as the available data.

Changes in the Walker circulation

Interest in this topic in the meteorological literature was conditioned by the fact that, independent of the biotic pump, it was rather robustly anticipated from global circulation models that the Walker circulation should slow down with global warming. The idea is that if the atmosphere gets warmer, it can carry more water vapor, such that if the vertical velocity does not change, the condensation rate is expected to increase proportionally to the water vapor content. This results in a higher rate of latent heat release in the ascending air. However, this heat must have time to escape to space (as thermal radiation) before the air descends back to the surface. Otherwise the circulation would have to push the still warm air parcels down performing work against the buoyancy forces. This would reduce the wind power and de-intensify the circulation. However, for the excessive heat to get lost the air must descend more slowly than it did before. Hence, in either case the air circulation should slow down. (Note however that these considerations do not take the condensation-driven dynamics into account, which can intensify, as more water vapor is available.)

Several lines of evidence suggest that in the long-term (during the last sixty years) the Walker circulation did become slower (Tokinaga *et al.*, 2012b,a). This was manifested as a decline in the sea level pressure difference between the eastern Pacific and the Maritime Continent, diminishing easterly wind velocities and a reduction in cloudiness (Tokinaga *et al.*, 2012b). On the other hand, a number of studies have been suggesting since early 2000s that the Walker circulation has been intensifying. These arguments used to be refuted on the bases that such a finding would contradict the existing models and could be due to a misinterpretation of the insufficiently accurate empirical evidence (see discussions by Chen *et al.*, 2002; Trenberth, 2002; Sohn and Park, 2010). But shortly after the paper in Nature of Tokinaga *et al.* (2012a) on the long-term slowdown of the Walker circulation, in 2013 there was a turnaround in the mainstream journals with the appearance of several studies highlighting instead its more recent intensification (L'Heureux *et al.*, 2013; Newman, 2013; McGregor *et al.*, 2014; England *et al.*, 2014). This finding was enrolled to explain the recent pause in global warming (absence of an increase of the mean global surface temperature in the last 15 years), which could not be explained by global circulation models either. It was argued that the accelerated Walker circulation enhances oceanic mixing such that the ocean takes in the excessive atmospheric heat more rapidly than it did before and offsets the global atmospheric warming (England *et al.*, 2014; McGregor *et al.*, 2014).

The data behind the argument about the Walker circulation intensification are the data on sea level air pressure, sea level height and low-level winds. These data do not allow one to unambiguously conclude about possible changes in the intensity of atmospheric moisture import to the Maritime Continent. However, they provide additional arguments to the statement that the Walker circulation is not powered by the east-to-west sea surface temperature differences. Han *et al.* (2014) found that in recent years the temperature difference increased between the tropical Indian and Pacific oceans. However, global circulation models forced with this difference produced the strongest acceleration of easterly winds west of 150°E, i.e. over the Maritime Continent. In reality over the most part of the Maritime Continent, except for PNG, the easterly winds actually slightly slowed down (de Boisséson *et al.*, 2014). The most significant wind acceleration is found in the Pacific ocean between 160 and 220 °E. In their analysis of robust wind patterns de Boisséson *et al.* (2014) found that the surface winds over the most part of the Maritime Continent became more westerly by 0-0.9 m s−1 (de Boisséson *et al.*, 2014, their Fig. 1b-d). Given that the winds of the Maritime Continent east of Sumatra are on average predominantly easterly (de Boisséson *et al.*, 2014, their Supplementary Fig. 1Sa), these data testify for a slowdown of the Walker circulation over the western part of the Maritime Continent, where the degree of deforestation is the largest. These data suggest a tendency for the air convergence center to shift to the north-east towards the oceanic precipitation maximum (Figure 44a).

Such a shift is not in disagreement with the findings of Tokinaga *et al.* (2012b) who argued in favor of the Walker circulation slowdown. Generally, as not all winds are accompanied by a non-zero moisture convergence, an increase in wind velocity does not necessarily imply an enhanced moisture convergence and vice versa.

More analyses and data are clearly needed to investigate the Walker circulation dynamics. If the long-term slowdown trend in wind velocities resumes this would mean a decreased rate of oceanic heat intake and an increased rate of global warming. So it is in the interest of the global community to study the possible role of forests on the Maritime Continent in these processes.

Changes in rainfall

Most data underlying recent analyses of the Walker circulation predominantly come from re-analyses (de Boisséson *et al.*, 2014). In simple words, re-analysis datasets are composed not by interpolation of the measured data but by using some atmospheric circulation model which calculates the missing data from the existing ones. If the model used does not capture well the studied phenomena errors will arise.

Atmospheric moisture convergence is known to be particularly poorly reproduced by models. Moist air arrives to land in the lower atmosphere, rises and becomes depleted of moisture (as clouds form and rain falls) (Figure 39). This dry air returns to the ocean in the upper atmosphere while the net imported moisture returns to the ocean via rivers. Air circulation models describe the aerial component of the water cycle: i.e. how much moisture is carried by winds. Measures of river runoff provide an independent check on any such models' validity, as this runoff must match what the winds bring in. In the oceans the models escape such a check, as there is no runoff to measure.

Current air circulation models do not pass this check: inputs don't match outputs. For the Amazon river basin the major reanalysis datasets only account for half the measured river runoff (Marengo, 2006). Similar considerable discrepancies are common for all regional models and no fix to this problem has yet been identified (e.g., Hagemann *et al.* 2011). As a recent example, Kumagai *et al.* (2013) using an atmospheric model concluded that aerial moisture convergence over Borneo is zero. From this it was concluded that the hydrological cycle on Borneo is reduced to recycling with precipitation equal to evapotranspiration $P = E$, $R = 0$. However, this directly contradicts the data on river runoff. River runoff on Borneo, while less than in PNG, amounts to over 1 m year^{-1} (Milliman and Farnsworth, 2011).

There is a tendency for the reanalysis datasets to show increased rainfall trends over many global regions that are inconsistent with runoff measurements and other independent observations. Pavelsky and Smith (2006) in their analysis of Eurasian river basins found that there is no correlation between the observed runoff trends and the rainfall trends from two main re-analysis datasets, NCEP and ERA-40. Both re-analyses indicated an increase in rainfall in the second half of the 20th century in the inner part of the Eurasian continent, while the runoff data showed an opposite trend. In contrast, the rain gauge data from the University of Delaware interpolation dataset was consistent with the runoff observations. Scientists cautioned against using re-analysis data in investigating trends in the hydrological cycle (Tokinaga *et al.*, 2012b).

The University of Delaware terrestrial precipitation dataset, based on rain gauge information, testifies for a significant reduction in the mean annual rainfall in Papua starting from approximately 1970 (Figure 38). This is in agreement with the trends for Borneo established by Kumagai *et al.* (2013) using the data from the APHRODITE's Water Resources Project (Yatagai *et al.*, 2012). There was a minimum in rainfall in the end of the 1990s coinciding with the strong El Niño and then a partial rebound from the minimum. Since the Tropical Rainfall Measurement Mission was launched in the end of 1997 (right before the rainfall minimum) this makes trend analyses using TRMM difficult to compare with rain gauges. However, according to As-syakur *et al.* (2013), TRMM data for 1998-2010 suggest a general decrease of rainfall over PNG. More independent rain gauge measurements are needed to verify the rainfall trends in the Maritime Continent.

The smaller-scale ocean-to-land moisture transport

The decline of the biotic pump functioning associated with deforestation can take the form of a decline in the moisture import from the adjacent ocean. According to the available satellite data the Maritime Continent receives a 30% higher rainfall than the adjacent ocean (As-syakur *et al.*, 2013). Notably, as discussed by As-syakur *et al.* (2013), this important feature is not reproduced by regional climate models, which instead suggest greater rainfall over the ocean. The difference in absolute magnitude amounts to about 1 m year^{-1}.

This is consistent with the data on rainfall on small tropical islands, whereby islands receive on average 10-30% more rain than the immediate ocean (Qian, 2008; Sobel *et al.*, 2011). But it was found that the Caribbean islands where the atmosphere is generally drier than over the Maritime Continent the rainfall surplus is significantly smaller in absolute terms than it is on the small islands in the Pacific. This is despite the fact that with less rainfall the temperature difference between the island and the sea (which is supposed to drive the rainfall surplus) is greater.

These data suggest that if the atmosphere over PNG becomes drier owing to deforestation, a significant reduction of rainfall in PNG may occur even in the absence of any changes in the large-scale air circulation. This change will be manifested as local shift of rainfall maxima away from land towards the coastal waters. (Note that as such a shift can cause an increase in rainfall over the adjacent ocean, the pattern can be misinterpreted as an intensification of the long-range moisture transport by the Walker circulation.)

Destabilization of the water cycle

An important feature of forest-regulated rainfall is its temporal uniformity: the biotic pump suppresses severe fluctuations and eliminates rainfall extremes like prolonged droughts or floods. McAlpine *et al.* (1983) noted that rainfall is PNG is very reliable, with interannual coefficient of variation less than 20%. The rainier regions like the central Highlands and the Sepik plain have a variability of less than 15%, while the drier regions like Port Moresby have more variable rainfall in both the wet and dry seasons. These patterns are consistent with data from other regions of the world. Millán *et al.* (2011) noted the very small day-to-day coefficient of variation in Ecuador rainforests. Ehleringer (1993) observed that in more arid regions the interannual coefficient of variation rises exponentially with decreasing annual precipitation.

Rainfall uniformity is of exceptional importance for PNG agriculture. Because of the complex terrain, gardening in PNG is often made on steep slopes. Coupled with a very high annual rainfall one could expect, by comparison with other world regions, a high rate of soil erosion. However, the soil erosion rates are comparatively low. Sillitoe (2006) investigated the traditional land use in the Southern Highlands Province of PNG and found that the relatively low soil erosion rates, even when gardening is performed on the steep slopes, can be explained by the fact that while rainfall is abundant, it arrives in a regular fashion. Devastating storms with daily precipitation in access of 100 mm day^{-1} are extremely rare. Rainwater from mild, regular rains is readily absorbed by soil. The infrequent strong storms cause landslides that are associated with significant soil losses (Sillitoe, 2006). Thus rainfall destabilization provides a great threat to PNG soils.

The stability of the water cycle can be evaluated considering the dynamics of the soil moisture store. We will now consider how this stability can be undermined by deforestation. The soil moisture store M is increased by precipitation P and depleted by evaporation E and liquid runoff R. The store of moisture in the atmosphere M_a is reduced by precipitation (which removes water vapor from the atmospheric column) and increased by evaporation and atmospheric moisture convergence C. The water budgets of soil and atmosphere are

$$m = P - E - R; \quad m_a = -P + E + C; \qquad (2)$$

where m and ma are the rates at which the two soil moisture store change. For the long-term averages we have $m = m_a = 0$ and $P = E + R$, $R = C$: the import of water to land via the atmosphere must be equal to the export of liquid water to the ocean (Figure 39).

The soil moisture store, which is of the order of 10^3 mm, is always more than one order of magnitude higher than the store of moisture in the atmosphere, which is in the order of 40 mm in atmospheric columns above the rainforest (Makarieva *et al.*, 2014b). The turnover time of atmospheric moisture is about ten days. On a longer time scale $m_a = 0$ and

$$m = C - R. \qquad (3)$$

To investigate the stability of the water cycle we need to specify the dependencies of P, R, C and E on soil moisture store M. Evaporation is limited by the flux of absorbed solar radiation and cannot depend on M at large values of M. However, at small M starting from completely dry soil with $M = 0$, evaporation increases with increasing soil moisture store from $E = 0$ at $M = 0$. This behavior can be described by an exponential function (Figure 49a):

$$E = E_{max}(1 - \exp[-M/M_E]). \qquad (4)$$

For $M > M_E$ we have $E = E_{max}$. The value of M_E characterizes the minimal level of soil moisture beyond which the plants can sustain a high evaporation flux independent of the amount of soil moisture.

Liquid runoff depends on soil moisture store in a similar way: it is zero for dry soil, grows with increasing moisture content and reaches a maximum when soil is comletely moist (the value of M is maximum, $M = M_R$):

$$R = R_{max}(1 - \exp[-M/M_R]). \qquad (5)$$

According to the biotic pump mechanism, evaporation E induces rainfall and atmospheric moisture convergence. The dependence of the atmospheric moisture convergence on soil moisture can thus be written as:

$$C = bE. \qquad (6)$$

The strength of the biotic control of the water cycle is described by two parameters, M_E in Eq. (4) and b in Eq. (6). The smaller the value of ME, the broader the range of soil moisture values $M_E < M < M_R$ where plants can maintain a high evapotranspiration. Coefficient b describes the strength of the biotic pump at a given value of evaporation. For large regions covered with rainforests $b \approx 0.8$ (moisture convergence is approximately equal to evaporation).

The stability of the water cycle can be described by potential function U, which describes how fast soil moisture content changes for a given value of M:

$$-\partial U/\partial M \equiv m = bE - R. \qquad (7)$$

A minimum of the potential function with $\partial U/\partial M = 0$ describes a stable stationary state, while a maximum describes an unstable state. Function U is defined to the accuracy of an arbitrary integration constant.

The potential function U (7) for different values of b is shown in Figure 49b for $M_E = 0.1M_{max}$ and $R_{max} = 2E_{max}$. With $b = 1$ there is a stable state with $M = 3M_E$, i.e. in the interval of soil moisture values non-limiting plant functioning.

With decreasing b the minimum becomes shallower and at $b = 0.6$ it moves outside the optimum interval $M_E \leq M \leq M_{max}$. For yet smaller $b < 0.4$ the only stable solution is at $M \approx 0$, which characterizes a desert (Figure 49b). The ratio of depth ΔU to width ΔM of the potential well in Figure 49a characterizes the mean rate at which the system tends to return to the stable equilibrium for a given M. The deeper the well, the stronger the external forcing must be to drive the system away from the equilibrium (i.e. in the direction of either droughts or floods). The ratio $(\Delta M)^2/\Delta U$ characterizes the time needed for the system to return to equilibrium after a disturbance of magnitude _M. The deeper the well (the larger the value of ΔU), the more quickly the system relaxes back to the equilibrium $M = M_0$.

For $b \sim 1$ it is equally difficult to drive the forest to either drought ($M = 0$) or flood ($M = M_{max}$). With decreasing M the equilibrium value of M diminishes and the potential well becomes more shallow with respect to the transition to the desert state. This means that those external forcings, at large b, were unable to drive the forest towards the drought conditions, are now able to do so. Moreover, the relaxation time towards the equilibrium has grown: i.e. once got to the desert conditions the forest can remain there for a longer while.

The value of b corresponding to $M_0 = M_E$ describes a threshold beyond which a further decrease in b causes significant changes in forest functioning, as the photosynthesis begins to drop towards zero. Deforestation reduces the value of b and, after a critical value has been reached, can initiate a self-destructing cascade of desertification. If we assume that for an intact forest cover $b = 1$ and that the regional value of b is proportional to the area occupied with intact forest cover then we can see that a forest reduction of about 30% can already draw the country towards a very dangerous change in precipitation regime. Given that deforestation in the Maritime Continent in Indonesia has come close to this mark, the on-going deforestation in PNG can become the last straw that would initiate the transition.

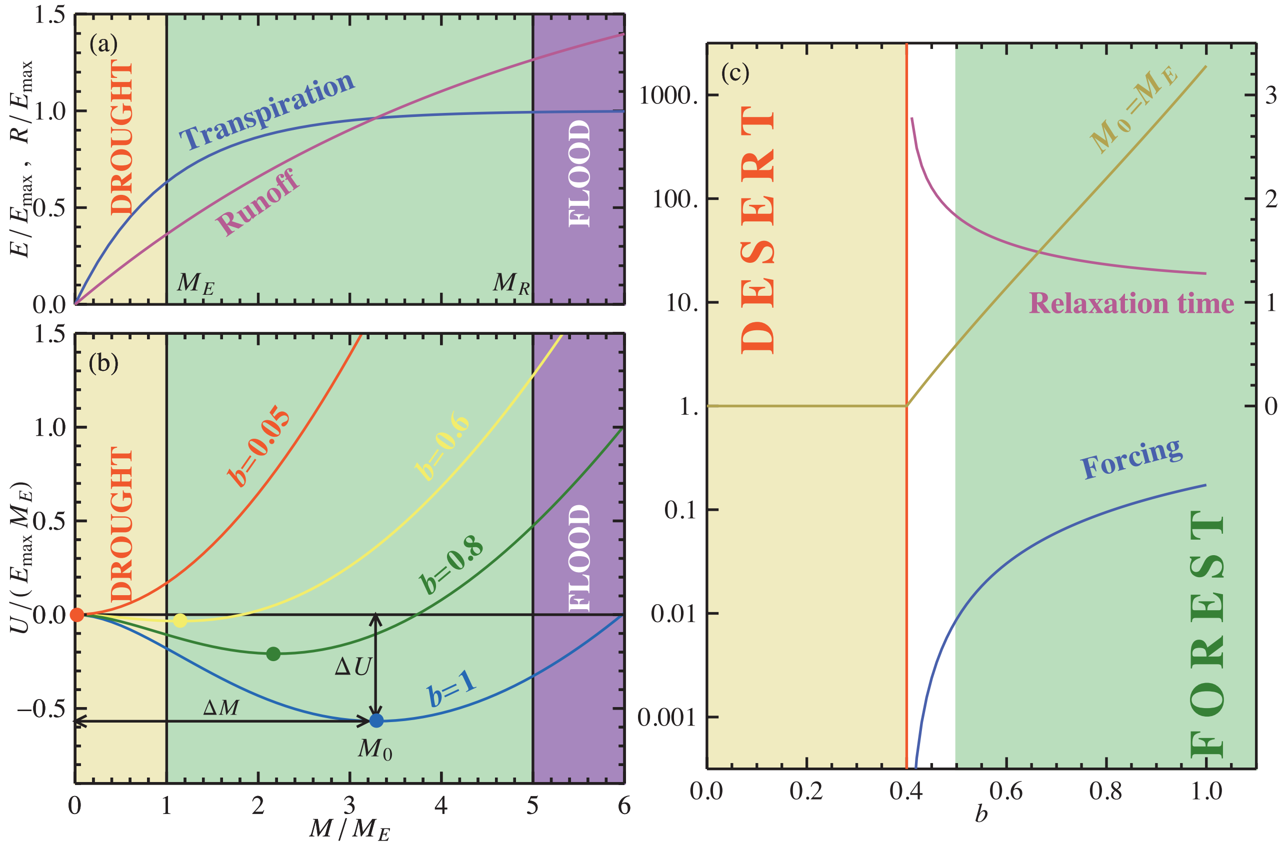


Figure 49. Stability of the soil moisture store M ensured by the biotic pump mechanism. (a) The dependence of dimensionless evapotranspiration E/E_{max} (Eq. 4) and runoff R/E_{max} (Eq. 5) on soil moisture store M in units of M_E (Eq. 4) for the case $R_{max} = 2E_{max}$, $M_R = 5M_E$. (b) Lyapunov potential function $U(M)$ (Eq. 7) for different values of biotic pump strength parameter b that relates atmospheric moisture convergence to forest evapotranspiration (Eq. 6). Drought and floods correspond to $M < M_E$ and $M > M_R$, respectively. For $b \sim 1$ the stable value of soil moisture store M_0 is within the interval of optimal plant functioning: $M_E < M_0 < M_R$. (c) The dependence of M_0 (right vertical axis) on the biotic pump strength parameter b. With $b \leq 0.4$ the only stable solution is $M_0 = 0$ (desert state). The left vertical axis refers to the dependencies of the mean time of relaxation from a desert state to M_0 , $-\Delta M^2/\Delta U = -M_0^2/U(M_0)$, and mean minimal forcing needed to push the system towards the arid conditions, $-\Delta U/M_0$. Note the logarithmic scale on the left axis. With decreasing b, the relaxation time grows (the system takes longer to return back to equilibrium from arid conditions), while the minimal forcing diminishes (it is easier to drive the system out of equilibrium). The white area describes the transition between the forest state with $b > 0.6$ and desert state with $b < 0.4$.

Pristine versus successional forests

The key to the stability of soil moisture is the ability of plants to keep transpiration within a broad range of soil moisture amounts $M_E < M < M_{max} >> M_E$. Since runoff decreases with decreasing soil moisture more rapidly than do evaporation and moisture convergence ($M_R > M_E$), this leads to a replenishment of soil moisture after any fluctuations that would occasionally reduce it. Likewise, if the soil moisture store is occasionally increased beyond the optimum, an increase in runoff at stable moisture convergence returns the moisture store back to the optimum. In this respect, pristine forest tree species differ markedly from desert plants as well as from early pioneer species.

In arid environments evapotranspiration by plants strongly depends on moisture availability in a similar way: plants transpire a lot of moisture during short rainy periods and spare moisture during the prolonged periods of droughts (Ehleringer, 1993). A similar reaction is found in early pioneer species in rainforests (i.e. those species that appear first on deforested sites and initiate forest succession). For example, in a study of early and late stage tree species in French Guiana Huc *et al.* (1994) found that during the dry season the pioneer species reduce leaf conductance of water vapor and transpiration by 30-50% compared to the rainy season. Meanwhile the late stage trees either do not reduce transpiration at all or the reduction is much less pronounced. This can be achieved by trees with a well-developed root system, which allows them to assess water stores at deeper soil horizons. Unlike the more arid ecosystems, equatorial rainforests keep transpiration constant or even increase it during the dry season (Nepstad *et al.*, 1994; Huete *et al.*, 2006; Saleska *et al.*, 2003; Poveda and Salazar, 2004; Ghazoul and Sheil, 2010; Davidson *et al.*, 2011; Restrepo-Coupe *et al.*, 2013).

This explains an important dichotomy in the functioning of desert and rainforest plants. In arid-land plants that generally are less “wasteful” in terms of water vapor, a high water use efficiency is associated with low growth rate and low productivity and vice versa (Ehleringer, 1993). Therefore, transpiration falls more rapidly than does photosynthesis rate among arid plants. In rainforest trees, conversely, higher water use efficiency is associated with higher productivity, which is often found in early successional trees. Late successional trees while having lower growth rates possess transpiration rates similar to those of the pioneer species (Nogueira *et al.*, 2004).

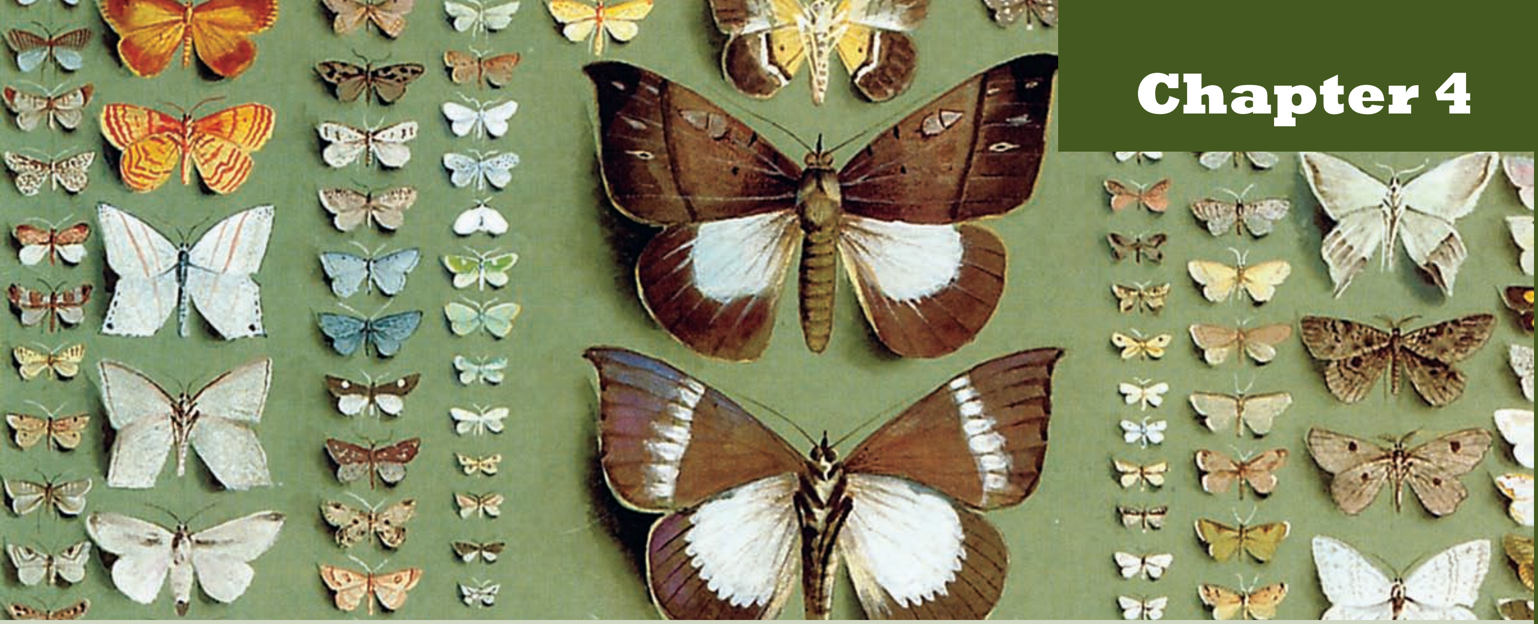
In the framework of viewing the forest as a biochemical complex-programmed reactor that controls rainfall, the right tree composition is key for its normal functioning. Under normal conditions successional species are found on gaps formed after pristine forest trees fall down. With a gap turnover time for tropical forests of the order of 100 years (Saulei and Swaine, 1988), at any moment of time successional species should normally occupy a minor portion of the forest area. The replacement of natural pristine forests by large disturbed areas occupied with successional trees (or alien species) represents a significant disturbance to the biotic pump functioning which precise magnitude has yet to be estimated. Eden (1974) observed that drying and savannization of the landscape in PNG may occur following the removal of forest cover by burning and cutting even in those places where originally the weather conditions favored forest growth.

Summary and conclusions

A stable and abundant precipitation regime is a cornerstone of PNG well-being. Recent scientific studies suggest that it is to a large degree controlled by the natural forest cover of the Maritime Continent, with deforestation expected to produce a decline in long-term average rainfall and an increase in hydrological extremes (droughts and floods). In line with these predictions with between a quarter and a third of the intact forest cover deforested or degraded since 1970 the long-term annual rainfall in PNG has reduced by about 15% (Figure 38), although the accuracy of the long-term rainfall estimates can be improved as more local meteorological information becomes available. In 1997 the country was hit by a drought worst in its history (McVicar and Bierwirth, 2001; Spinoni *et al.*, 2014). Analyses of the stability of water cycle indicate that the decline of rainfall upon deforestation is not linear but may occur precipitously and probably irreversibly once a certain threshold in forest degradation is reached (Figure 49).

The forest-mediated import of moisture from the ocean to feed biological productivity in PNG occurs on a small scale from the oceans adjacent to PNG territories as well as on a much larger scale as part of the moisture flux brought from the eastern Pacific by the Walker circulation (Figure 45). Long-term observations suggest a slowdown of the Walker circulation in the last 60 years and a growing predominance of El Niño conditions (Tokinaga *et al.*, 2012b). In the recent two decades, however, there is some evidence of an intensified Walker circulation with a displacement of rainfall maxima away from the Maritime Continent. This intensification is thought to be responsible for the negligible rise in global surface temperatures observed in recent years. If this connection is confirmed and the Walker circulation continues to slow down in the long term, the rate of global warming may accelerate. Deforestation diminishes the condensation rate and thus will impose an El Niño-like impact on the regional rainfall. The role of condensation across the Maritime Continent in these scenarios remains to be quantified and it is considered as a major challenge for atmospheric sciences.

The accumulated body of evidence unambiguously justifies urgent efforts on elaboration of a scientifically advanced and comprehensive national strategy of forest and environment conservation. With its forests Papua New Guinea hosts a grandiose biochemical reactor of enormous power which creates and regulates rainfall in one of the most important energetic hotspots of the Earth's climatic system. The meteorological data from PNG, including the hydrometeorological characteristics of the forest cover, have an exceptional global value. An active position of PNG state in this question has the potential of attracting resources and assistance from the rest of the world. A nation-wide program coordinating gathering and analysis of such data using the already existing meteorological networks and developing new ones in PNG is in the interest of the global community. As a major threat for the ecosystems of PNG comes from population growth (Ningal *et al.*, 2008; Butler *et al.*, 2014; Laurance *et al.*, 2011) these opportunities could help the country to optimize its demography towards sustainability and ensure the long-term well-being and climate security for the PNG nation.



Chapter 4

Ecological research in Papua New Guinean rainforests: insects, plants and people

Vojtech Novotny[1, 2] and Pagi Toko[1]

Vojtech Novotny co-founded and directs the New Guinea Binatang Research Center, a non-profit organization devoted to biodiversity research, conservation and education in PNG. He is also Head of the Department of Ecology and Conservation Biology at the Biology Centre of the Czech Academy of Sciences and a Professor of Ecology at the University of South Bohemia. He is interested in the ecology of tropical rainforests, biodiversity conservation, and ecological education in tropical countries, particularly Papua New Guinea where he has been active for the last 20 years.

Pagi Toko is an entomologist working as the deputy director of New Guinea Binatang Research Center, a PNG based non-profit organization specializing in biodiversity research, capacity building and conservation. He is also the country representative of the Association of Tropical Biology & Conservation, an international organization that promotes biodiversity research, education and conservation. He is interested in the tropical ecology of insects and biodiversity conservation. He holds a Master of Science degree from the University of Papua New Guinea.

Ecological research: why in Papua New Guinea?

New Guinea, one of the largest tropical islands, remains covered by the third largest rainforest in the world (after the Amazon and the Congo Basin). Papua New Guinea (PNG) is therefore suitable for the study of biological variability within large, continuously forested areas, across a range of soil, hydrological and climatic conditions. PNG biologists can still build research stations in forests with largely intact vegetation and vertebrate fauna (Figure 50). In contrast, researchers at some of the most active research stations in the tropics, including the Barro Colorado Island in Panama, La Selva in Costa Rica, or Lambir Hills in Malaysia, have access limited to forest fragments or defaunated forests (e.g., Harrison *et al.* 2013).

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[1] New Guinea Binatang Research Center, PO Box 604, Madang, Papua New Guinea

[2] Biology Center, Czech Academy of Science and the University of South Bohemia, Branisovska 31, Ceske Budejovice, Czech Republic

Figure 50. Field research infrastructure in PNG: (A) the Swire Research Station in the centre of the Wanang Conservation Area, with a 50-ha lowland forest dynamics plot that is following the individual fate of 288,204 plants (details at www.entu.cas.cz/png/wanang); (B) Wanang paraecologists Ruma Umari (front) and Jonah Filip (back) rearing insects from rainforest fruits at the station. Photo M. Leponce (A) and V. Novotny (B).

PNG is one of the few countries in the Old World tropics in possession of complete rainforest altitudinal gradients, where continuous forest spans from the lowlands to its natural limits at about 3,700 m. There are several such gradients along the Central Cordillera, including Mt. Wilhelm, as well as in the Finisterre Mts., another, geologically younger range. The altitudinal gradients at both Mt. Wilhelm and the Finisterre Mts. have been recently opened for research (e.g, Sam *et al.* 2014, Freeman *et al.* 2013), coordinated by the New Guinea Binatang Research Center and the Tree Kangaroo Conservation Project respectively. Both transects rely on access agreements with local landowners, and so far comprise only temporary field camps. They have the potential, if developed further, to become internationally important research facilities, particularly for the study of the effects of climate change on biodiversity.

Long altitudinal gradients in humid tropics also represent globally important maxima of species diversity, generated by rapid change in species composition with altitude. Mt. Wilhelm is ranked among the seven most species-rich areas in the world for plants, with >5,000 species per 10,000 km2 (Barthlott *et al.* 2007). Our studies show that almost a third of butterfly and half of bird species from PNG fauna live on the slopes of Mt. Wilhelm (Table 5), mostly in unprotected forests outside of the Mt. Wilhelm National Park.

Table 5. Diversity of plants, insects and vertebrates along a complete rainforest altitudinal gradient (200 – 3700 m asl.) at Mt. Wilhelm. S_{tra} – total number of species recorded at eight study sites along the transect, S_{max} – maximum species diversity per site, A_{max} – altitude (in m) where local diversity reaches its maximum, S_{tot}/S_{max} – ratio of transect to maximum diversity, S_{tot} – the number of species in PNG or New Guinea (*Ficus* spp.: NG from Weiblen 2006, butterflies: PNG from Tennent 2006, ants: NG from Antweb 2015, frogs: PNG from AmphibiaWeb 2015, birds: PNG mainland from Sam & Koane 2014), S_{tra}/S_{tot} – the proportion of regional fauna found along the Mt. Wilhelm transect.

Taxon	S_{tra}	S_{max}	A_{max}	S_{tra}/S_{max}	S_{tot}	S_{tra}/S_{tot}	Reference
Ficus spp.	70	49	700	1.4	151	0.46	L. Sam unpubl.
butterflies	247	140	200	1.8	924	0.27	Sam 2011
geometrids	892	327	1200	2.7	?	?	Toko 2011
leafhoppers	450	138	200	3.3	?	?	Dem 2011
ants	232	104	700	2.2	782	0.30	Moses 2014
frogs	54	17	1700	3.2	367	0.15	Dahl 2011
birds	238	113	200	2.1	465	0.51	Sam & Koane 2014

PNG provides biologists with ample supply of islands of various sizes and degrees of isolation from the main island, allowing researchers to study the effects of habitat fragmentation on forest ecosystems. Islands, as nature's replicated experiments in the evolution and ecology of natural ecosystems, have inspired many researchers, including the founders of evolutionary theory C. Darwin and A. R. Wallace. The islands in PNG played a smaller, yet significant role in the history of science. Their ants inspired E. O. Wilson's theory of the taxon cycle, describing sequential phases of expansion and contraction of species ranges (Wilson 1961). J. Diamond developed the concept of the "checkerboard distribution" of species when he found that certain combinations of potentially competing bird species never occurred together on the same island (Diamond 1975). We can reasonably expect more discoveries awaiting ecologists upon the hundreds of New Guinea islands.

New Guinea: an island with a complicated history

The island of New Guinea is important biogeographically, as it comprises the majority of all tropical rainforests within the Australian biogeographic region, and an even larger majority in the newly recognized Oceanian zoogeographic region (Holt *et al.* 2013). It has a highly complicated geological history (Toussaint *et al.* 2014, Ufford & Cloos 2005), to the delight of some and despair of other biologists. The southern part of the island is a part of the old and stable Australian craton, floating slowly northwards on the Australian tectonic plate. Southern New Guinea is therefore technically a part of Australia, or, if we choose to focus on biodiversity rather than land area, we may prefer to see Australia as a southern province of New Guinea. New Guinea and Australia form a single land mass, also called Sahul or Meganesia, at the time of low sea levels, such as during the last ice age 18,000 years ago. The northern part of New Guinea existed originally as a collection of islands, pushed towards the Australian craton by the movement of the Pacific tectonic plate. The islands floated towards, and finally crashed into the craton, assembling what is now northern New Guinea as a jigsaw puzzle of terranes of various ages. The crashes also lead to the uplift of the Central Cordillera, as well as a number of smaller, and younger, montane ranges in the northern part of the island. The latest such collision, 3.0-3.7 million years ago, uplifted the Finisterre Mts., which is therefore PNG's youngest montane range, still growing at the geologically rather impressive rate of 0.8-2.1 mm per year (Abbott 1995, Abbott *et al.* 1997). This complicated history is likely to have contributed to increased speciation, since both islands and high mountains are well known generators of species. The importance of geological history was difficult to test using the contemporary distribution of species (Polhemus & Polhemus 1998, De Boer & Duffels 1996), but recent phylogenetic analyses of speciation history point to the importance of the past in explaining the high present-day diversity of insects, and likely also other taxa (Toussaint *et al.* 2014).

While only one in every 1,000 people in the world is Papua New Guinean, as many as one in every 20 species of the world's plants and animals live in PNG (Sekhran & Miller 1995). The country's 5%, largely endemic, share of biological diversity (including, for instance, 924 butterfly species from the global total of approximately 18,000 species; Table 1), and its 12% share of language diversity (Lewis 2009, Novotny & Drozd 2000), makes Papua New Guinea more important in the world for its diversity than its economic impact, based mostly on the production of 3% of the world's gold, 2% of its copper, 3% of its coffee and 1% of its palm oil. The key question remains whether Papua New Guineans will be able to look after the wealth of biodiversity in their own country, particularly as it is coming under increasing threat.

Given the biological potential of the country, could we envisage PNG becoming prominent in ecological research? Before dismissing this notion as over-optimistic, if not plainly unrealistic, let us consider two events in PNG history. In 2013, cargo transported throughout PNG by air represented an utterly negligible share of the global total (0.003%). It may therefore come as a surprise that less than a century ago, in the 1930s, Guinea Airways carried more freight by air, from Lae to Bulolo goldfields, than the rest of the world's airlines put together. The Bulolo – Wau area experienced another unusual operation thirty years later, in 1961, when J. L. Gressitt, an entomologist from the Bishop Museum in Honolulu, founded the New Guinea Field Station, later known as the Wau Ecology Institute. In the 1960s and 1970s, Wau became the home of one of the largest entomological research projects in the Pacific, if not the world, creating the world's largest collection of PNG insects. It is housed at the J. L. Gressitt Center for Research in Entomology, established by the Bishop Museum shortly after Gressitt died in a plane crash in China in 1982.

Discovering and naming Papua New Guinea's species

Papua New Guineans have, in their 850 local languages, hundreds of names for each of their Cassowary species, as well as for other birds. At the same time, local names for insects are scarce, despite the forests teeming with insect life. Modern taxonomists show similar bias towards cassowaries, all of which were properly named as early as 1860, over insects. Even today, an afternoon walk in any New Guinean forest will bring encounters with many insect species that are unknown to science. Even expert biologists cannot answer simple questions about insects, the questions any curious child might ask, such as how many insects species are living in the forest around us, and in Papua New Guinea overall, or what would happen to the forests if all the insects suddenly vanished.

The Queen Alexandra's Birdwing, *Ornithoptera alexandriae*, the largest butterfly in the world, living only in parts of the Oro Province and increasingly endangered by encroaching oil palm plantations (Parsons 1992), is the PNG's most famous insect species. The type specimen (used to describe the species, and to resolve any future questions about the species' identity) was collected by Albert Meek, an English naturalist (Meek 1913). He used a shotgun to get a high flying female; the bullet holes are still visible in the wings of the type specimen, described in 1907 by a renowned collector Walter Rothschild and later donated to the Natural History Museum in London, together with almost a million of other Rothschild's butterflies (Ackery 1997).

Until recently, types and other museum specimens, inspected in person by taxonomists, often provided the only safe means of identification for new material. For instance, in our study of 272 species of large moths (Macrolepidoptera), 60% of species were identified and taxonomically well known, but only half of this number was sufficiently well described in the literature so that a museum visit to see specimens was not necessary (S. E. Miller, pers. comm.). This situation is particularly inconvenient for tropical countries, where insect collections are difficult to maintain, and the type material for their fauna is often kept overseas, as is the case for *O. alexandriae*. The largest collection of PNG insects is almost 7,000 km away, at the Bishop Museum in Honolulu.

Fortunately, the taxonomy of tropical insects is entering a revolution fuelled by molecular techniques, particularly DNA barcoding (Miller 2007, 2015), combined with the availability of images of species and interactive keys via internet. The DNA barcode is a sequence of 648 bases in the mitochondrial cytochrome c oxidase 1 (COI) gene that has the right mutation rate – neither too low nor too high - that can be used for the identification of individual insect species, each of them typically characterized by a unique COI sequence. Barcoded individuals can be grouped into putative species, each given a stable numerical identifier (BIN, or barcode index number), used for preliminary classification of species (Ratnasingham & Hebert 2013). A complete library of COI sequences for insect species in PNG would allow quick identification of newly sampled specimens. Comprehensive barcode databases are now being built, particularly in the species-poor temperate zone countries with well known fauna, but also in Australia (Hebert *et al.* 2013). Barcode of Life (www.boldsystems.org), an on-line database, comprises 2.5 million barcodes from 200,000 insect species, sent there from all over the world. PNG, with almost 31,000 insect barcodes, ranks amongst the leading 15 countries (BOLD 2015), mostly due to the joint activity of the New Guinea Binatang Research Center and the Smithsonian Institution (Figure 51).

The COI sequences combined with morphological descriptions and high-resolution digital images, published on-line, can simplify formal descriptions of large numbers of new species, providing at last a feasible method for the description of insect diversity in PNG in the foreseeable future. This concept of "turbo-taxonomy" is being explored by research team with PNG participation (K. Sagata) and using PNG insects (Tanzler *et al.* 2012, Riedel *et al.* 2013). PNG does not need molecular laboratories to implement it, since DNA barcoding is being done mostly by a few specialized laboratories, whose services are used by many countries. What PNG needs is in-country expertise in the analysis and taxonomic use of barcode information so that it could be combined with internet databases and collections into tools for identification of PNG insects. Examples of online resources for PNG insects include the BOLD database, key to the forest insect pests (Schneider 1999), Ants of New Guinea (Janda 2015), Caterpillars feeding on New Guinea plants (Miller *et al.* 2015), a key to ambrosia beetles (Hulcr 2015), and a web site on New Guinea insects (http://www.papua-insects.nl/).

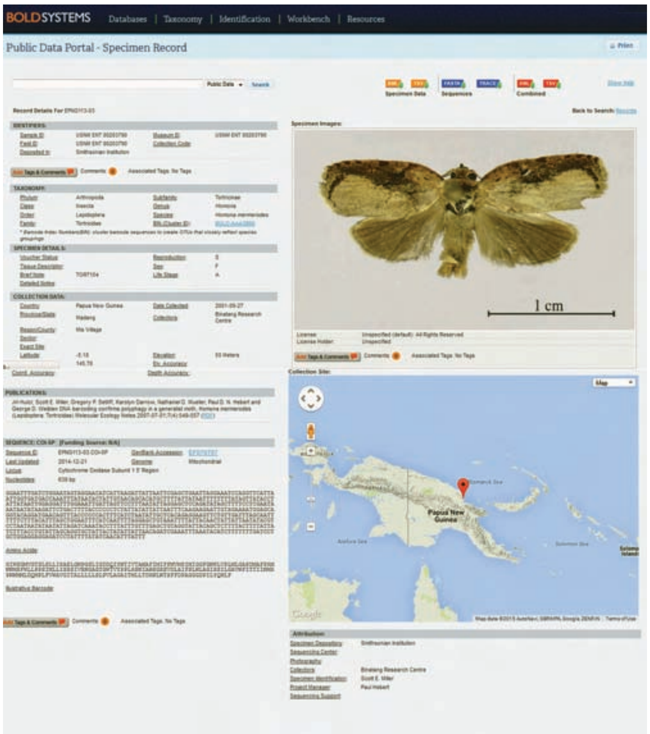


Figure 51. Molecular and morphological resources for the taxonomy of PNG insects available on-line: a specimen page for Homona mermerodes (Tortricidae) in the Barcoding of Life database, providing public access to DNA sequences, images and geographic location of the specimen (http://barcodinglife.org/index.php/Public_RecordView?processid=EPNG113-03).

Insect diversity: travelling from local to global estimates

Butterflies (Papilionoidea) are perhaps the only insect group rich in species and well known taxonomically, in PNG (Parsons 1999) and elsewhere in the tropics. The fastest growth of knowledge of PNG butterfly species took place early, from 1850 to 1900, the time of numerous expeditions to New Guinea by mostly European naturalists, including A. R. Wallace (1858), L. M. D'Albertis (1872), A. B. Meyer (1873), F. H. H. Guillemard (1883), H. Fruhstorfer (1891), W. Doherty (1892) or H. C. Webster (1894), all of them interested in butterflies. This intense interest led to almost half of all PNG butterfly species being known as early as in 1900 (Figure 52). The pace of discovery slowed after 1920 to a steady rate of 2.5 – 3.0 new species per year that has been maintained for 90 years, until the present day. Discovering a species new for PNG is rather more difficult than in other insect taxa. This is good news since it qualifies butterflies as a suitable model group for ecological studies. The study of ants, in comparison, started later than butterflies, experienced a similar boom at the turn of the 20th century and a slow-down in more recent years. Rather surprisingly, the species accumulation curve gives no hint of the fact that the PNG diversity that remains to be described is far greater in ants than in butterflies.

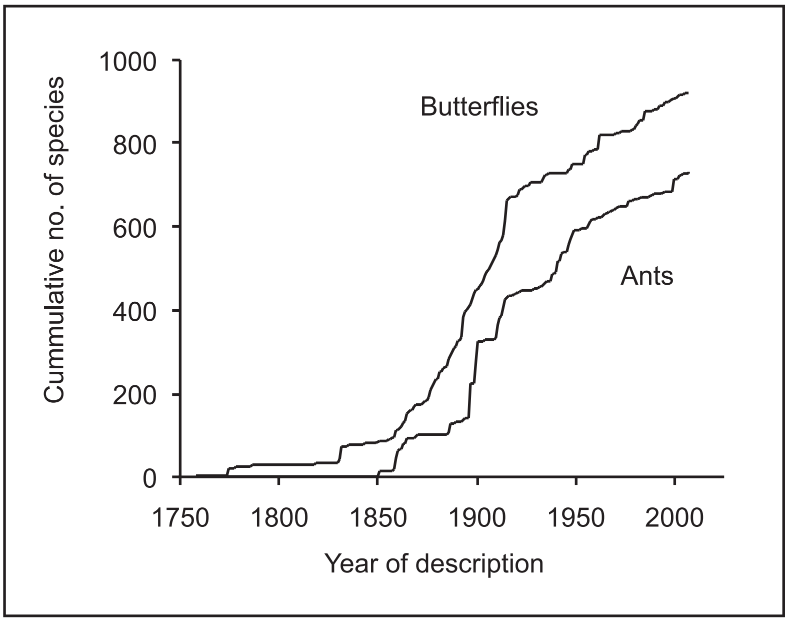


Figure 52. Cumulative total of presently recognized species of butterflies from Papua New Guinea (data from Tennent 2006) and ants from New Guinea.
(data from Antweb 2015).

Butterflies are a good model group also because they are interesting to the general public. The monitoring scheme in Great Britain, for instance, includes the country's 59 species (note that it would be difficult to find a single site in PNG that would be as poor in butterflies as to only match the entire fauna of Great Britain), runs since 1976, covers over 1,500 sites and counted more than 16 million butterflies (http://www.ukbms.org/). Such detailed monitoring of a few species may seem boring and unnecessary, but the scheme has provided invaluable information on the population decline of endangered species, as well as changes in species distribution ranges and seasonality in response to climate change and habitat disturbance (e.g., Dennis 1993). In contrast to Great Britain, PNG butterflies are monitored at only a single site, at the Swire Research Station in Wanang (Basset el al. 2013). Unlike the British, obsessed with butterflies, Papua New Guineans do not have a similar tradition of amateur biologists who could volunteer for broader surveys. There is at least one village, Swagup on the banks of the Sepik river, that has another insect, the praying mantis, as a totem animal, so hope remains that Papua New Guineas might yet convert to butterfly worship as the British have done. Failing that, many schools located in remote rainforest areas could become, with appropriate training, centres for simple butterfly surveys that could become an interesting teaching tool for biological education. PNG used to be one of the leading countries in insect farming and trade, which provided income to village-based collectors, selling mostly butterflies and beetles through the Insect Farming and Trading Agency. Regrettably, this small-scale, conservation-friendly business (Slone *et al.* 1977, Orsak 1993) has collapsed in the past decade.

Unfortunately, butterflies are an aberration in the taxonomic knowledge of PNG insects. Many insect taxa remain almost completely unknown to science. L. Baje, a University of PNG student, decided to study leafhoppers from Typhlocybinae subfamily, a group of small, plain looking insects sucking on plant leaves that are difficult to identify and thus ignored by just about everybody. She sampled 65 tree species in Madang and discovered 47 typhlocybine species, most of them specialized to a single tree species (Baje *et al.* 2014). She estimated their "effective specialization" at 0.3 for PNG, which means that each plant species should have, on average, 0.3 unique typhlocybine species feeding on it. There are at least 10,662 plant species in PNG (listed by Hoft 1992, and excluding orchids that have virtually no herbivores). This number, multiplied by effective specialization, gives us the estimate of 3,554 typhlocybine species feeding on PNG vegetation. However, only 40 species, i.e. less than 1.5%, have been taxonomically described from PNG, and only 4,508 species are known globally. Typhlocybines thus exemplify a taxonomically almost completely unknown group of herbivores. Many other taxa in PNG remain unknown, mostly those with small body size. For instance, only seven from 119 species of parasitoid wasps, reared from caterpillars, were already known taxonomically (Hrcek *et al.* 2013 and pers. comm.). We can still study communities of these species, using arbitrary names or numerical codes instead of species names, but such data sets cannot be combined into a country-wide database. This is why insect ecology in the tropics is heavily biased towards the study of communities, rather than broader geographic patterns.

L. Baje was not the first biologist to use plant-based extrapolation to estimate the diversity of insects. Westwood (1833) multiplied 100,000 vascular plant species, believed at that time to grow on the entire planet, by 4 - 6 unique insect species per plant, from his studies in Britain, to estimate the global diversity of insects at 400,000 – 600,000 species. Erwin (1982) applied the same approach 150 years later to his data on 682 beetle species sampled by applying insecticide to the canopies of 10 *Luehea seemannii* trees in Panama and calculated, after corrections for host specificity, arthropod taxa other than beetles, and non-canopy species, that there were 30 million insect species on the global flora of 50,000 tree species. We have used data on the number of insect herbivores feeding on almost 100 tree species in PNG and recalculated the global insect estimate again, suggesting that there are 6.1 million species (with a 90% confidence interval of 3.6 – 11.4 million species) of insects on Earth (Novotny *et al.* 2002; Hamilton *et al.* 2010, 2011). This estimate, supported by other studies (Odegaard *et al.* 2000, Miller *et al.* 2002), has been widely accepted. Our best estimate of global diversity of insects thus relies on the insect data collected in three PNG villages near Madang town: Ohu, Baitabag and Mis.

Rainforest food webs: insect herbivores, their host plants and their enemies

Ohu, Baitabag and Mis villages have hosted 15 years of insect studies, the former two in their community-based forest conservation areas. This research sampled insects feeding on tree species representing all main plant lineages: *Gnetum gnemon* from the gymnosperms, species representing the basal angiosperms, monocots including palms and gingers, and the two main lineages of eudicots: rosids and asterids. It also included herbivorous insects living many different lifestyles; the so called guilds are groups of species feeding on the same plant part in the same manner. And so we set off to study one guild after another: insects feeding as adults or larvae on leaves, semi-concealed larvae in rolled leaves, mining larvae chewing tunnels inside leaves, gallers chemically manipulating plants to produce galls, sap-sucking insects piercing individual leaf cells, or phloem, or xylem vascular elements, larvae boring in the phloem or xylem part of wood, or using wood to grow fungi as food, as well as larvae feeding on roots, and on fruits – either fruit pulp or seeds. Some of these guilds have been rarely studied before. For instance, adult chrysomelid beetles feeding on leaves are well known, while their larvae, feeding on roots, are not since nobody likes digging in the mud. R. Pokon, a PNG University of Technology student, avoided that necessity by setting up traps catching adult beetles freshly emerging from the soil, and traced them back to the roots they fed upon as larvae. He discovered that the larvae were mostly generalists, feeding on many different tree species, and showed how important these soil-dwelling chrysomelids were: there were about 200,000 of them emerging from each hectare of the forest every year (Pokon *et al.* 2005).

The three villages near Madang presently have 31 research papers listed in Google Scholar (2015) to their credit, and have become the world's most comprehensively studied sites for a wide range of insect herbivore guilds (Novotny *et al.* 2010, 2012). This research allowed us to study rainforest plant-insect food webs. They map the abundance of each plant and herbivore species and the frequency of their trophic interactions, i.e. which insect species feeds on which plant species, and how often (Figure 53). Over the years, we sampled 1,500 herbivore species and traced nearly 7,000 feeding interactions with their host plant species. However, even these seemingly impressive figures represent only 15% of the total herbivore species and trophic interactions in a lowland forest. We estimated that the entire rainforest plant – insect herbivore food web comprised ~50,000 distinct trophic interactions between ~200 plant and ~9,600 herbivore species (Novotny *et al.* 2010). The food web in Figure 53 may look complicated, but it shows only 251 trophic interactions, i.e. 0.5% of the total that may be found in a single rainforest.

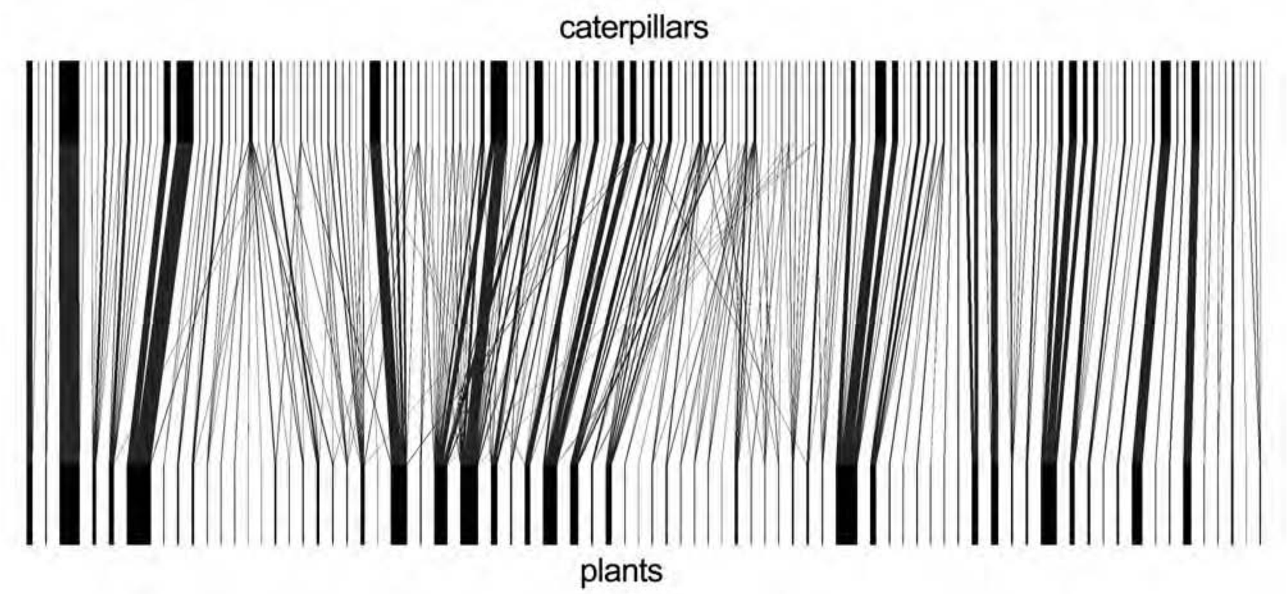


Figure 53. Plant-herbivore food web for 151 species of leaf-rolling and leaf-tying caterpillars feeding on 88 plant species in a lowland New Guinea rainforest. The lower bars represent the frequency with which each host plant is consumed by herbivores and the upper bars represent herbivore species in proportion of their abundance. The widths of the links are proportional to the frequency of each interaction. Data from Novotny *et al.* (2010).

Such complexity is not good news for tropical ecology. Ecologists should be able to explain how all these species coexist in the same forest, and predict how they will respond to disturbance, such as removal or addition of certain species. At present, we are unable to make these predictions from the knowledge we have. However, we can play with the food webs experimentally, change them in various ways and see what happens, hoping that we could understand the mechanisms of observed changes. PNG is a perfect place for manipulative rainforest experiments. Large forest areas are felled every year for subsistence agriculture. Most landowners are happy to try ecological experiments instead of gardening, as long as the discovery of fundamental ecological principles pays better than growing sweet potatoes for the nearest market. One of such experiments is described later in this chapter (Klimes *et al.* 2011).

How can so many species coexist in a tropical rainforest? This is one of the fundamental questions of ecology that keeps ecologists awake at night. The fascination of ecologists with high diversity in the tropics is partly due to the fact that many of them grew up in species-poor countries of the northern temperate zone. From such vantage point, rainforests may seem particularly diverse and exotic, while this perspective is not necessarily shared by PNG ecologists. However, the coexistence of almost 10,000 herbivore species in the same forest does require an explanation, even for an unprejudiced Papua New Guinean mind. A large number of herbivore species can be supported either by equally diverse plant resources (bottom-up effects), or by natural enemies that keep all herbivore species at low population densities, reducing thus their mutual competition for resources (top-down effects) (Denno *et al*. 2005). The number of distinct resources available to herbivores depends on plant diversity and host specialization of herbivores. It is well known that plant diversity is highest in the tropics (e.g. there are 5–10 times more plant species per 10,000 km^2, and six times more woody species per hectare in tropical than temperate areas; Novotny *et al*. 2006; Barthlott *et al*. 2007), but it remains unclear whether plant diversity is the only factor driving insect herbivore diversity.

Secondary forests, in PNG and elsewhere, have greatly reduced diversity of plants. Since the number of herbivore species per plant species remains the same between primary and secondary forests (Leps *et al*. 2001), this impoverishment of vegetation is driving the diversity of herbivorous insects. Further, secondary forests appear to support greater abundance of caterpillars (Whitfeld *et al* 2012). Given the extent of forest conversion that is taking place in New Guinea, the possibility of increased abundance of caterpillars poses a challenge for forest management, especially where pest outbreaks may threaten forest regeneration after logging.

Herbivores species are feeding on fewer plant species in tropical than temperate forests (Forrister *et al*. 2015), and higher specialization may thus facilitate their coexistence in tropical forests. However, we found no difference in host specificity between leaf-chewing insects in PNG and European forests, as long as it was measured on sets of plants with the same phylogenetic diversity in each forest (Novotny *et al*. 2006). It is thus possible that narrow host ranges in the tropics are driven by the composition of tropical vegetation, particularly by its many rare species of plants. The diversity of herbivores can be also maintained by top-down control, by their natural enemies. This is particularly likely when an increase in population density of herbivore species leads to higher mortality from their natural enemies, for instance because it is easier for them to focus on a more abundant resource.

Mosquitoes and malaria: a density dependent regulation of human populations in New Guinea?

Positive density-dependent mortality might have also been important in regulating human populations in PNG. Lowland populations are more resistant to malaria than the Highlanders, partly because they carry several red blood cell mutations. These are mildly harmful for the ability of blood to carry oxygen, but also protect against malaria (Clark & Kelly 1993, Kwiatkowski 2005). A high frequency of these mutations in the lowlands suggests that malaria protection afforded by the mutations is more important than their negative health effects, which points to malaria as an important mortality factor. In malaria-free areas the mutations disappear quickly, as they have done in the Highlands. Malaria probably controlled human populations in a density-dependent manner, since its transmission by Anopheles mosquitoes becomes more efficient in dense human populations. Higher transmission causes higher mortality from malaria, reducing the population density, and thus also returning malaria transmission to low levels. This mechanism may explain, together with differences in soil fertility, why the population density in PNG peaks in malaria-free montane valleys at 1700 m asl, while the lowlands remain sparsely populated (Muller *et al*., 2003). Differences in population density shape other aspects of human societies, explaining perhaps why are the highlands societies more competitive and readier to fight for scarce resources that are those from the lowlands (Wiessner & Pupu, 2012). Differences in the competitiveness of lowland and highland populations are manifested in many ways; for instance, all taxi drivers in the lowland capital city, Port Moresby, are from the Highlands, as they have out-competed everybody else. For a biologist, the connection between the *Plasmodium malaria* parasite, frequent tribal wars in the Highlands and the predominance of Mt. Hagen taxi drivers in the capital city is rather straightforward indeed. Malaria research, including work on the malaria vaccine, is also an active area of PNG research, based at the PNG Institute of Medical Research (e.g., Muller *et al*. 2003, Genton *et al*. 2003).

The top-down impact of predators on insect herbivores is difficult to study since the acts of predation are hard to observe in the field. However, any defenceless insect exposed on rainforest vegetation – such as a termite worker glued to a leaf – is quickly discovered and attacked by ants; how quickly can be measured, as an index of predators' activity. For instance, 15% of such tasty baits were discovered and attacked within 30 minutes (Novotny *et al.* 1999). Another experiment pinned hundreds of artificial caterpillars, made of children's modelling clay, on leaves and monitored attacks by ants and birds, leaving recognizable marks on the clay caterpillars from their attacks. We found that caterpillars were increasingly safe at higher elevations, and that while ants were the most dangerous enemies of plasticine caterpillars in the lowlands, birds become more important at elevations above 1,500 m (Sam *et al.* 2014).

The importance of ants in lowland forests, where they seem to be literally everywhere, leads to an intriguing and seemingly naive question: how would a lowland rainforest look and function if all of a sudden, its ants disappeared? We tried to answer this question by an experiment in a 25 x 25 m forest plot. We isolated the plot from the surrounding forest by felling a narrow strip of vegetation along the perimeter and cutting lianas overlapping into the plot, then fenced the plot using plastic sheet coated with insect glue, and hung 135 traps, accessible only to ants and containing tuna laced with insecticide, in the canopy of all larger trees. We managed to reduce the number of ants in the forest by 80% (Klimes *et al.* 2011). After 10 months of the experiment, we sampled insect herbivores and measured the damage they had done to the plants. Rather surprisingly, the ant exclusion did not lead to any increase in herbivore abundance or damage. The missing ants could have been compensated by higher predation by birds, or ants may not be such important predators as previously thought. Although they quickly attack any available baits, they may be less successful attacking real insects. Ants also obtain energy from plants, directly from extrafloral nectaries or indirectly from honeydew produced by sap-sucking hemipteran insects. A pioneering study using isotope analysis of ant biomass that can distinguish between plant and animal origin of carbon and nitrogen discovered that rainforest ants obtain a large share of energy from plants (Davidson *et al.* 2003). Our ant exclusion demonstrates the importance of experiments in the study of complicated food webs in tropical forests, where seemingly logical theoretical expectations are not always confirmed by real plants and insects.

Plant diversity may very well sustain herbivorous insect diversity, but the opposite relationship, where insect herbivores (or other plant enemies, such as fungal pathogens) control plant diversity, is also possible and intensely discussed by ecologists. Explaining high rainforest diversity is even more difficult for plants than insects, since plants all have very similar essential requirements: water, sunlight, and soil nutrients. With 536 plant species growing within a 50-ha forest plot in PNG (Vincent *et al.* 2014), it is quite difficult to envisage 536 distinct niches, determined by unique combinations of environmental conditions, needed for coexistence of all plant species. Top-down control by natural enemies is thus more likely in plants than insects, and insect herbivores could be one of the density-dependent mortality factors providing such control. This mechanism was proposed independently by D. Janzen and J. Connell almost half a century ago (Janzen 1970, Connell 1971). It can be inferred indirectly from spatial patterns of plants in forest plots (Bagchi *et al.* 2011), or tested by excluding plant enemies by insecticides and fungicides (Bagchi *et al.* 2014). We have reared insects, including beetles, moths, and fruit flies, from 3,500 kg of fruits sampled from 531 rainforest plant species (Figure 50a) and found that insect attacks on fruits are too rare in most of the plant species to cause the seed mortality needed for the density-dependent mortality effects hypothesized by Janzen (Ctvrtecka *et al.* 2014). We can thus cross off seed-eating herbivores from the list of likely suspects for top-down control of plant diversity in PNG forests.

Rainforest research of insect herbivores, and their enemies, has obvious forestry and agricultural applications. In particular, many cash crop trees, including coffee or cocoa, are alien species in PNG that has become targets for insect herbivores from local rainforests. For instance, we have reared cocoa pod borer (*Conopomorpha cramerella*), a major pest of cocoa (Yen *et al.* 2010), also from several rainforest tree species (unpubl. data). The colonization of introduced tree species by herbivores can be observed on two alien species spreading in PNG on their own: *Piper aduncum* from South America, and *Spathodea campanulata* from Africa (Figure 54, Figure 55). They remain limited to disturbed and secondary forest vegetation, as predicted by ecological theory (Leps *et al.* 2002). Both alien species were quickly colonized by local herbivore communities that reached diversity comparable with the herbivore diversity on native plant species, but composed predominately from generalists (Bito 2007, Novotny *et al.* 2003). We can expect similar process for tree crops.

Figure 54. *Piper aduncum* (light green) invading secondary forest in the Bulolo region.

Figure 55. The invasive species *Piper aduncum* (light green) invading grassland and scrub in the Bulolo region.

Coffee and betel nut in New Guinea: benefactors or parasites?

Seeds, as packages of valuable nutrients ready to support a germinating embryo, tend to be well protected against predators, mechanically by hard shells or chemically by a variety of poisons. In some cases, this protection can be hijacked by seed predators for their own benefits. The PNG economy relies on such "misuse" of two poisons: caffeine, an alkaloid originally used by Coffee shrubs in Africa to protect their seeds against predators, and arecoline, used together with a mix of other alkaloids to protect seeds of *Areca catechu* palm (Wink 1993, West 2012). In both cases, these chemicals became unexpectedly attractive to one seed predator species, namely humans. This relationship may be seen as an example of mutualism, where both humans and plants benefit. In particular, coffee and betel palm reached population sizes and geographic distributions that would have been impossible without human assistance. An alternative interpretation of human relationship with the two plants suggests that the plants are the only beneficiaries here so that both coffee and betel palm are parasitizing on humans, chemically manipulating millions of human brains to ensure that people would spare no expense and effort for the benefit of these two plants, planting them on huge areas of land, and protecting them from pests and competition by other plant species. A look at the streets of European cities, almost entirely given to coffee shops, or streets in PNG, lined with betel nut stalls, lends some credibility to the parasitism hypothesis.

Rainforest adventures of alpha, beta and gamma diversity

The 924 butterfly species in PNG represent the pool of available species, produced by in situ evolution or immigration, from which local communities can be drawn. Alternately, we can see the PNG fauna as an aggregate of all local butterfly communities. Its size, or gamma diversity, depends on the species richness of individual communities (alpha diversity) and change in species composition among communities (beta diversity). PNG butterflies may form either locally species-rich communities that do not change too much from one site to another (high alpha and low beta diversity scenario), or species-poor communities unique in composition at each site.

Beta diversity in insect communities is a composite result of dispersal limitation, depending on the geographic distance, and differences in environment between sites. There is little surprise that herbivore species change with changes in the composition of vegetation. That is why we focused on a more interesting case of herbivore communities feeding on the same plant species, and explored the effect of dispersal limitation in ecologically uniform lowland forests. Our team of six researchers descended on eight study sites forming a regular grid within a 500 x 150 km area in the floodplains of the Sepik and Ramu rivers and, together with local villages, completed three months of insect sampling at each site. We found low beta diversity of insects feeding on the same plant species, even for sites 500 km apart that still shared 70% of their caterpillar species (Novotny *et al.* 2007). Lowland herbivore communities may be locally very diverse, but they do not change much from one area to another. In other words, they have high alpha but low beta diversity.

We also caught 5,903 live butterflies at one of the study sites, marked each with a personal number written on its wings, and released them again. Then we managed to catch 1,803 of them again and see how far they had moved since their previous capture. The butterfly species moved 184 m on average, but in six of the 14 species studied, >1% of individuals moved 1 km or more (Vlasanek *et al.* 2013). In view of this mobility, travelling 500 km through continuous rainforest should not be a problem, certainly not during 18,000 years available for travel since the end of the last ice age.

Beta diversity should be much higher in the forests along steep environmental gradients, such as elevational gradients. At Mt. Wilhelm, the mean annual temperature drops 0.54 °C with each 100 m gain in elevation so that the rainforests there are experiencing mean temperatures from 27.3 °C (200 m asl) to 8.6 °C (3,700 m asl), across less than 50 km distance. Six students went to Mt. Wilhelm to study altitudinal biodiversity trends in their favourite animal groups: Legi Sam surveyed butterflies (Papilionoidea) flying along transects, Pagi Toko sampled geometrid moths (Geometridae) attracted to light, Francesca Dem used sweep net to sample leafhoppers (Auchenorrhyncha) from the vegetation, Jimmy Moses sampled ants (Formicidae) by various methods using baits and pitfalls, Chris Dahl conducted night surveys of frogs, and Katerina Sam studied birds by point counts and mist netting. Together they found 2,113 species (Table 1). While most taxa reached their maximum alpha diversity in the lowlands, geometrids and frogs were most diverse at mid-elevations. The ratio of total diversity along the entire transect to the local maximum ranged from

1.8 to 3.3, suggesting that environmental variability generated by changes in altitude enriched Mt Wilhelm species pool by 80 – 230% compared to even the most diverse community at a single altitude. Mt. Wilhelm represents a nationally important biodiversity hotspot, with 15 – 51% of all PNG species present in the taxa where such analysis could be performed. Although important, the species counts do not tell the whole story. For instance, butterflies are most diverse at 200 m and decrease steadily with elevation to 2 species at 3,700 m, but the species with the smallest geographic ranges, and thus of highest conservation concern, prefer higher elevations (Sam 2011).

Ecological research and the conservation crisis in Papua New Guinea

The permanent forest dynamics plot in Wanang does not look it, but it is probably the most expensive infrastructure for ecological research ever built in PNG. It is the only member of the Center for Tropical Forest Science, an international consortium of plant plots (www.ctfs.si.edu), from the Australian biogeographic region. The 1.0 x 0.5 km plot is situated in the centre of the Wanang Conservation Area, a 10,000 ha rainforest on the Ramu River floodplains owned and managed by eight clans from the Wanang village. The plot comprises 288,204 plant stems with diameter >1 cm, all of them individually tagged, measured, mapped and identified to 536 species (Vincent *et al*. 2014) so that the precise distribution of each species can be studied (Figure 56). The plant data are also linked to regular surveys of selected insect taxa, including butterflies, ants, termites, and fruit flies in the plot.

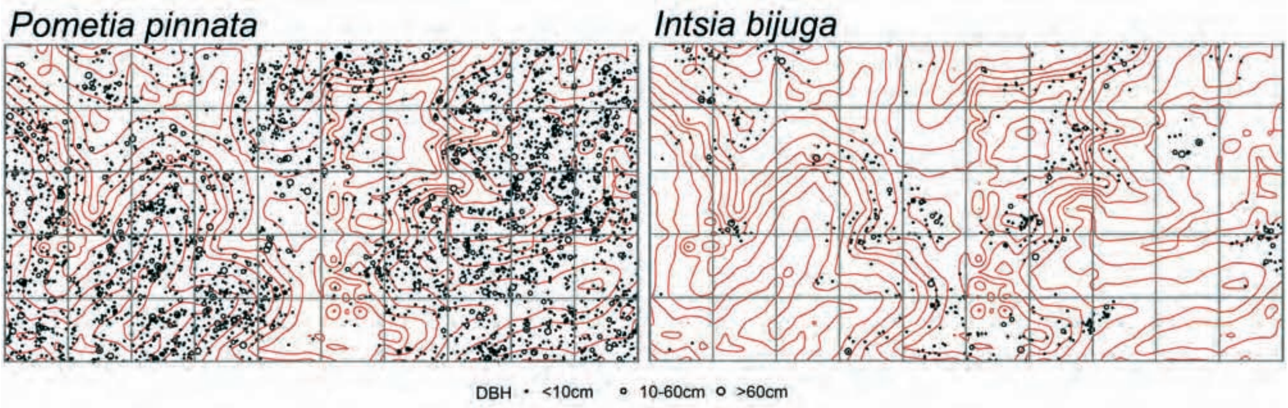


Figure 56. Spatial distribution for two important tree species in the 50 ha Wanang forest dynamics plot: (A) *Pometia pinnata* (Sapindaceae), species with edible fruits, known as taun, and (B) *Intsia bijuga* (Fabaceae), commercially valuable species, known as kwila. The map shows that *P. pinnata* prefers lower slopes while *I. bijuga* prefers ridges (Vincent *et al*. 2014).

The tagging of the trees took a team of six researchers three years of steady work, and used over 500 kg of aluminium tags, nailed or tied to each plant stems in the forest by over 50 km of copper wires. The list of all tagged trees would fill ten books 500 pages each, although this would not be a particularly exciting read. The plot will be re-surveyed every five years so that we can study changes in the forest growth and composition. Which trees grow faster, which suffer high mortality, how does the terrain, or the tree neighbours, affect growth and survival, is overall forest biomass or carbon stock increasing, how does it respond to El Niño? There are many interesting question to ask with such a large data set.

Wanang Conservation Area: a recipe for conservation success?

Adjacent to the 50 ha forest dynamics plot is the Swire Research Station: three permanent buildings with laboratory and accommodation space, and autonomous water and solar electricity systems, built from 15 tons of material dropped by a helicopter in the middle of the forest (Figure 50). The station is accessible from Madang by a three hour drive followed by a three hour walk. The plot, research station and conservation area are a result of collaboration between Wanang village, the New Guinea Binatang Research Center, the PNG Forestry Research Institute, the University of PNG, the Department of Environment and Conservation, Swire and Sons, and the Steamships Trading Company, with links to overseas academic partners in USA (University of Minnesota, Smithsonian Institution) and Europe (Czech Academy of Sciences, University of South Bohemia). The collaboration achieved a synergy between rainforest conservation, research and training. In particular, research activities provide steady employment for Wanang villagers and pay conservation royalties, therefore financially supporting the landowners' decision to conserve, rather than log, their forests. This rainforest conservation is also attracting private funds for community development projects, including a village school.

Not all PNG conservation can be supported by income from research, but a funding mechanism that rewards landowners for conservation, similarly as they are rewarded for the use of their lands for timber or mineral extraction, is crucial for the future of conservation in PNG (Novotny 2010). Conservation looks deceptively inexpensive since, when successful, it means that not much happens to the protected forest. In fact, the real cost of conservation equals the potential profits that could be generated by alternative uses of the forest: conservation's opportunity cost. The cash-generating schemes proposed for conservation include ecotourism, sustainable harvest of rainforest products, or agriculture, such as coffee or vanilla farming. These have proved economically unviable, and/or required full time work by the landowners, making them unattractive in comparison to logging royalties. The PNG government should recognize that landowners conserving the country's biodiversity play equally important role as those allowing the extraction of the country's mineral and timber resources, and reward both land use with appropriate royalties.

PNG is entering a critical phase in its development that will determine, probably within a single generation, the fate of the country's environmental wealth. The dynamics of land use in neighbouring countries provides examples of possible trajectories for PNG. In particular, while selectively logged forests after the first cut remain biologically valuable, they are often subject to degradation through premature repeated cuts and finally conversion to plantations, as illustrated by rapid deterioration of the majority of lowland forests in Borneo (Reynolds *et al.* 2011). In contrast, Australia demonstrates that there is a point in economic development when tropical forests become valued by the society to the extent that their conservation is widely supported. The key issue for PNG is whether there will be enough forests left when the country reaches this point of economic and political development. There is no global correlation between the country's wealth and the proportion of its land under forest cover (Gapminder 2015), suggesting that logging is not a secure path to economic development. Unlike many other developing countries, PNG has an alternative to large scale logging and forest conversion in its highly profitable mining industry that generates several orders of magnitude higher revenue per hectare of impacted land than is the case for logging and plantation industries.

PNG is one of the few countries in the world where customary ownership of the land, originating in a tribal past, is recognized by the country's legislation and an enforceable reality on the ground. This land tenure makes conservation areas difficult to negotiate, as they may include numerous landowner groups with different priorities and expectations. However, the same is true for logging projects, and these have been negotiated much more successfully than conservation areas. As a result, PNG has an impressive network of logging concessions, while the network of protected areas to conserve the country's biodiversity is rudimental (Shearman & Bryan 2010).

Conservation is driven primarily by biologists who are concerned that conservation areas are situated in biodiversity hotspots. Starting with the PNG Country Study on Biological Diversity (Sekhran & Miller 1995) and the PNG Conservation Needs Assessment (Beehler 1993), we have seen 20 years of prioritizing different regions of the country for some hypothetical future conservation that would be, one day, miraculously delivered to its biodiversity hotspots. There has been many failed conservation projects in the PNG history, all due to inadequate popular, political or financial support for conservation and ensuing conflicts about the use of land (West 2006, Mack 2014, Novotny 2009, 2010). There are hardly any conservation projects that have failed because they lacked adequate biodiversity information and were therefore erroneously protecting a species poor forest. This experience tells us that conservation areas should be located primarily where conservation enjoys strong support from the landowners. The Wanang Conservation Area, for instance, exists because it has been spearheaded by an effective community leader, Filip Damen, later recognized for his leadership qualities also internationally, as a recipient of the Seacology Prize (www.seacology.org/about/seacology-prize/). We should embark on a broad search for the communities supporting conservation, places where we can find leaders of similar calibre as Mr. Damen, and ensure fair economic compensation of landowners for conservation efforts. In the longer-term perspective, training more PNG biologists and developing more education- and a more research-oriented society in general may be the most efficient path to better conservation (Mack 2014). Conservation measures need to be formulated, explained to, and promoted in the general population for them to succeed politically. These tasks are there for both present and future PNG biologists.

Ecological research in Papua New Guinea: how to make it better?

The progress in the enormous task of mapping and understanding biodiversity of PNG has been rather slow, even considering that PNG has a small population and is not a particularly wealthy country. For instance, "Papua New Guinea" featured in the title of 397 papers in non-medicinal biological research published in 10 years from 2003 to 2012 (and listed in Web of Science, an international database for research papers), compared to 1023 papers on Costa Rica, another developing tropical country with a small population. Even more importantly, only 95 papers on PNG, i.e. one quarter of the total, had at least one PNG author, while almost a half of papers from Costa Rica had a local author. The minority role of PNG researchers in the study of their own country's biodiversity is also a concern for conservation, which needs a vibrant local academic community to support it politically. PNG has the potential to produce a strong cohort of research biologists in the next generation since its population is predominately young (a consequence of rapid population growth, 2.7% annually; Laurance at el. 2012), English-speaking, and continues to be knowledgeable about the natural environment, typically as a result of a rural, village-based adolescence.

Declining language skills and ecological knowledge in New Guinea: a case for concern?

The rainforest dwelling societies, in PNG and elsewhere, are well known for detailed knowledge of the natural environment, including classification and ecological knowledge of their plants, birds and mammals (e.g., Majnep *et al.* 1978, Majnep & Bulmer 2007). High cultural diversity in PNG is a product of the past tribal isolation and as such can become impractical in modern life.. While PNG languages still thrive in the village environment, only 52% of respondents were fluent in their local language among urban internet users, compared to 95% of their parents (Baro 2015). Baro (2015) also documented that ethno-biological knowledge is linked to fluency in local language, and as such also in decline, even in many remote villages.

There is probably no other country in the world with a young generation as comfortable in the rainforest environment as PNG. This extensive rainforest experience has presented an opportunity to develop paraecologist training programmes in PNG, combining the experience from rainforest living with science-oriented education in research techniques. Over the past 20 years, PNG has become one of the two leading countries in paraecologist training and research, together with Costa Rica (Basset el al. 2000, 2004, Janzen 2004, Simons 2011). This programme is lead by the New Guinea Binatang Research Center and contributed to the majority of recent entomological research in PNG, including almost all studies discussed in this chapter. Paraecologists are trained in general science, collecting methods, specimen preparation, microscopy, photography, computing, logistics of biodiversity surveys, and principles of resource conservation. Further, they can became experts on local flora and fauna, and constitute efficient teams for biodiversity surveys. The paraecologist programmes have potential to build a large and qualified workforce that, in collaboration with researchers and students, can significantly advance the study of PNG biodiversity.

Postgraduate students are the driving force of biodiversity research in developed countries, providing enthusiastic and inexpensive workforce as well as fresh ideas. In PNG, postgraduate education opportunities are extremely limited and expensive. It is striking how few Honours and MSc gowns can be spotted in the student crowd at the annual University of PNG, as well as other universities, graduations. The scarcity of postgraduate students remains the principal weakness holding back biodiversity research in PNG (Mack 2014). Many papers cited in this chapter were lead by postgraduate students from PNG (L. Sam, N. Baro, F. Dem, L. Baje, R. Pokon, P. Toko, C. Dahl) and overseas (K. Sam, P. Vlasanek, P. Klimes), illustrating the potential of students in research.

PNG research also suffers from the unfortunate split between universities, where excessive teaching loads leave the staff with little opportunities to engage in research, and research institutes, where researchers lack daily contact with postgraduate students. This institutional split could be bridged by having postgraduate students in residence at the research institutes, and researchers from these institutes as guest lecturers at universities. This approach to student training has been already tested by some NGOs as well as the PNG Institute of Medical Research. An International Cooperative Biodiversity Group project based at the University of PNG (Barrows *et al*. 2009) represents an example to follow in combining student training, biodiversity research and commercial applications.

PNG is in an excellent position to capitalize on its advantages for tropical ecology field work by providing suitable research facilities for ecological research, attracting both local and international researchers and students to biodiversity research. This role has been played over the past 50 years by a series of mostly non-governmental organizations, including the Wau Ecology Institute, the King Leopold III Biological Station, the Christensen Research Institute, the Sera Field Station of the Wildlife Conservation Society, the Swire Research Station of the New Guinea Binatang Research Center, the Kamiali Biological Field Station and the Motupore Island Research Station of the University of PNG. Most of these stations are no longer active, highlighting the instability of NGO driven facilities in PNG, dependent on overseas donors with ever changing priorities. A more stable field research facility could bring more overseas research to PNG with potential benefits, including opportunities for international collaborations, access to overseas facilities and student training.

Further, PNG is lacking a mechanism for funding biodiversity, and other, research that would be open to applicants from all universities, research institutes and NGOs, and award funds according to the merit of submitted research proposals, judged by an independent panel of researchers. Australia, UK and USA, among other countries, spent a lot of time testing the optimum methods for research funding and, rather remarkably, all converged on a more or less identical model, exemplified by their respective grant agencies: ARC, NERC, and NSF. Researchers in PNG would be well served by adopting this model. Finally, while there are research institutes focused on agriculture and forestry, the country is lacking a PNG Biodiversity Research Institute.

The PNG Government has recently begun to address the pressing issues of research funding, management and training through the PNG Research, Science and Technology Council, founded in 2013. These efforts have been noted and applauded in a "Papua New Guinea: Pacific Positivity" feature in Nature (Campbell & Grayson 2014).

In conclusion

Papua New Guinea remains a country "at the edge of the world", or, more precisely, the Pacific, where many global trends, both positive and negative, arrive with some delay. This is largely a good thing, allowing the country to learn from the successes and mistakes of others. The tsunami of rainforest exploitation that destroyed most of the forests of the continental Asia, then the Philippines, followed recently by Borneo, has now arrived to the shores of New Guinea. It is the present generation that will make decisions about the future of PNG biodiversity that will influence the country's trajectory for many years to come. Biological research in PNG has great, yet so far mostly unfulfilled, potential to expand, and help to steer the country towards informed decisions about its future. It is time for PNG biologists to go to work, to study and protect the country's biodiversity "from the mountains to seas".

Acknowledgements

We thank to S. E. Miller, Y. Basset, G. D. Weiblen, S. Segar and the staff of New Guinea Binatang Research Center for ideas and comments on the manuscript. The research was funded by the Czech Science Foundation (14-04258S), US National Science Foundation (DEB-841885), the UK Darwin Initiative for the Survival of Species (19-008), and Swire and Sons. We are grateful to PNG landowners for access to their lands, to the Department of Environment and Conservation for permitting our research, and to the University of Papua New Guinea for the support of students.

Occurrence and Status of Papua New Guinea Vertebrates

Allen Allison and Oliver Tallowin

Allen Allison is Senior Zoologist at Bishop Museum, Hawaii. His research interests focus on Papuan Herpetofauna. With more than 40 years of experience, he has organized and led numerous research expeditions to remote regions throughout New Guinea, including one with more than 100 personnel. He has travelled widely and visited field sites and field stations throughout Australia, Pacific Basin, SE Asia, Asia, including Japan and India, Europe, and North and South America.

Oliver Tallowin is a Ph.D candidate at Tel Aviv University. His research focuses on reptile ecology, biogeography and conservation. His interest is in the herpetofauna of New Guinea and conducting computer based modelling to elucidate patterns in species richness, range size and turnover.

Introduction

The forests of Papua New Guinea support some of the richest assemblages of vertebrates on the planet, and are home to least 1786 species of amphibians, reptiles, birds and mammals, a little over 5% of the world's total (Table 6). To put this fauna into broader perspective, Papua New Guinea has around twice as many vertebrate species as are known from the entire island of Borneo, a tropical landmass that is considerably larger, but has a similar array of forest types (Allison, 2009). Similarly, the vertebrate fauna of Papua New Guinea is about twice the size as that of the rain forests of West Africa, a land area nearly three times larger (Myers *et al.*, 2000).

Table 6 – Species Richness - Papua New Guinea and world vertebrates

	World	PNG	% of World
Amphibians	7,360	342	4.6
Reptiles	10,119	333	3.3
Birds	10,560	813	7.7
Mammals	5,416	298	5.5
TOTAL	**33,455**	**1,786**	**5.3**

This extraordinary diversity is especially impressive in view of the fact that the Papuan region (New Guinea to the Solomon Islands) is less well known than most other tropical areas in the world. Although the birds, which have a large scientific and public following and tend to be discovered and named far more rapidly than other vertebrate groups, are reasonably well known, other vertebrate groups, particularly frogs, remain poorly known (Figure 57), with many new species being discovered annually.

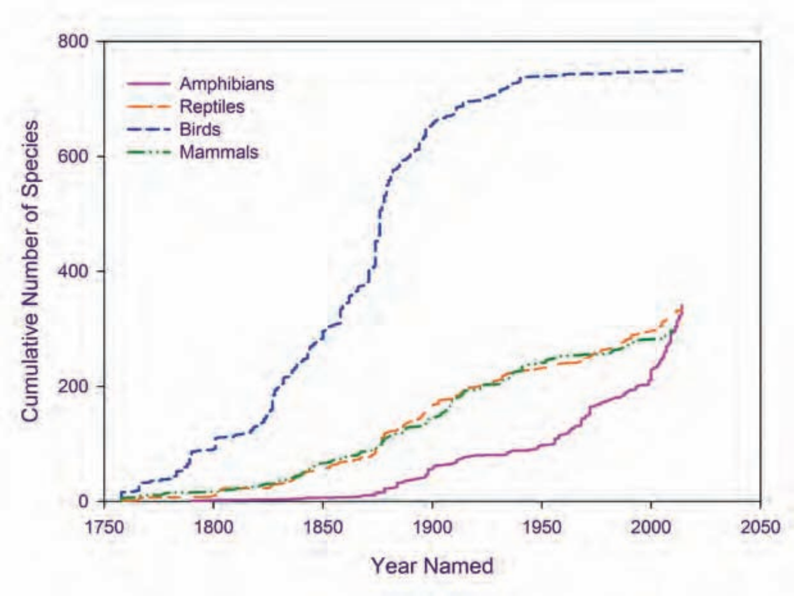


Figure 57. Comparative rates in the scientific naming of amphibian, reptile, bird and mammal species in Papua New Guinea.

At the current rates of discovery, it is likely that the number of mammals and reptiles known from Papua New Guinea will increase by around 25% and the number of frogs will double when all species are known. This will produce a final tally that will likely be similar to that for all of Australia, with similar numbers of birds and mammals, fewer reptiles, but many more species of frogs.

A high proportion of the vertebrates of PNG are endemic – i.e., they are found nowhere else in the world. For example 77% of the frogs are endemic to Papua New Guinea. Although only 98 (17.8%) of the 636 species of resident birds known from Papua New Guinea are endemic, a far greater number are endemic to the island of New Guinea or to the Papuan region. For example, of the 365 species of birds endemic to the island of New Guinea, 313 (85.7%) are found in Papua New Guinea.

Biological Exploration of Papua New Guinea

Although the trade in birds of paradise plumes between Asia and New Guinea extends back 5,000 years (Swadling, 1996), and European voyages of discovery had sailed along its coasts for centuries, the first significant efforts to document the New Guinea biota began with the establishment of Fort Du Bus at Triton Bay by Dutch colonial authorities in 1828. This helped attract the great naturalist, Alfred Russel Wallace to New Guinea and in 1858 he spent several months collecting insects and other animals at Dorey Bay (near present-day Manokwari on the Vogelkop Peninsula). Wallace published a well-received popular account of his travels in The Malay Archipelago (1869) which helped stimulate scientific interest in New Guinea.

The first collections from Papua New Guinea were probably made by William Dampier who in 1700 visited New Britain (Dampier, 1729). He was followed by several French voyages of discovery beginning in the late 1700s, two of which made collections from New Ireland in the early 1800s (Brosse, 1983). They also visited western New Guinea.

In spite of its close proximity to the British colony of Queensland, there was little significant exploration of eastern New Guinea until the coast was mapped beginning in 1872 by John Moresby in the Basilisk. His discovery of a fine harbour, which he named Port Moresby after his father, received considerable publicity and this brought others to New Guinea. In 1874 John Lawes of the London Missionary Society founded a base at Port Moresby. He helped establish friendly relations with the local people and Port Moresby became something of a gateway to the interior of eastern New Guinea.

In late 1874 an Italian naturalist, Luigi d'Albertis, established a base at Yule Island and made large zoological collections there and from adjacent parts of the New Guinea mainland. He returned to New Guinea in early 1876 and sailed up the Fly River in the steam launch Neva, claiming to have reached a point more than 930 km upstream. After returning to Europe in 1878, he described his exploits in a variety of papers and in two well-received volumes, What I Did and What I Saw (1880).

The biological exploration of New Guinea gained momentum in 1875 with the arrival of a large party of scientists aboard the Chevert, a three-masted sailing ship converted into a research vessel. The expedition was led and funded by William Macleay, a wealthy and socially prominent pastoralist from Sydney. However, the expedition met with limited success because of dissention within the crew and among the scientists, together with bad weather. Although Macleay described a number of new species of amphibians and reptiles from Kattow (Macleay, 1877a-d) on the Binituri River in what is now Western Province, few other scientific publications resulted from the expedition. A succession of more modest exploration followed.

The annexation of British New Guinea in 1884 and its conversion to a Crown Colony in 1888, together that same year with the appointment of William MacGregor as Administrator (later, 1899, Lieutenant-Governor) helped usher in an era of exploration. Similarly, the annexation of German New Guinea in 1884 helped stimulate exploration of northeast New Guinea and the adjacent archipelagos that today are part of Papua New Guinea.

The exploration of German New Guinea was initially dominated by a number of large, well-funded expeditions, often supported by ships. However, with only a few exceptions these were largely confined to coastal regions that were thought to have commercial potential for agriculture. In contrast, much of the exploration of British New Guinea focused on the remote interior. MacGregor had a strong interest in exploration and personally led a number of expeditions, including the first European ascent of Mt. Victoria in 1889 (MacGregor, 1890). He also helped independent naturalists and collectors reach remote parts of the Colony. In particular MacGregor facilitated much of the important collecting by A.S. Meek, A.F. Eichhorn and others beginning in 1894 supported by Walter Rothschild of the Tring Museum (Rothschild, 1983). The number of expeditions diminished after MacGregor left in 1898 for another colonial posting.

Most exploration activity came to a close with the outbreak of WWI and the occupation of German New Guinea by Australian forces. However, German scientists continued to work on the massive collections deposited in European museums and herbaria, with the result that northeast New Guinea, the adjacent Admiralty and Bismarck archipelagos, together with the island of Bougainville became far better known than the British colony of Papua.

After WWI the former German and British colonies were amalgamated as the Territory of Papua and New Guinea and were administered beginning in 1914 by Australia under a League of Nations Mandate. Biological field work, in what is today Papua New Guinea, slowly resumed and picked up momentum with the first of several major expeditions organized by American museums. The first of these, the Whitney South Seas Expedition by the American Museum of Natural History, collected in various parts of the south and southwest Pacific beginning in 1928 and continued intermittently until 1934 (Gregory, 1933; Chapman, 1935). They made extensive zoological collections from the Bismarck and Admiralty archipelagos, Bougainville and other islands in the Solomons chain. This was followed in 1929 by the Crane Pacific Expedition (Field Museum) which transported scientists to various islands of the southwest Pacific in a large yacht, the Illyria. They visited the Solomon Islands, New Britain, northeast New Guinea, and several places in western New Guinea (Shurcliff, 1930).

In 1933 the American Museum of Natural History was back in New Guinea with support from Richard Archbold in the first of seven Archbold Expeditions (Archbold and Rand, 1935). The initial expedition worked along an altitudinal transect from Yule Island and the adjacent part of the SE coast to the summit of Mt. Albert Edward, spending 13 months in New Guinea. This was followed by the Second Archbold Expedition, of the same duration, that focused on the Fly River basin but also visited Daru Island. The expedition's mammologist, G.H. Tate, also collected mammals in the Laloki Basin and along the Kokoda Track (Archbold and Rand, 1940).

Fieldwork virtually ceased during WWII, although a few servicemen, notably Philip Darlington, made important collections while serving in the military (Wilson, 1991). Shortly after the end of WWII, E. Thomas Gilliard of the American Museum of Natural History made the first of a series of expeditions to Papua New Guinea. He primarily collected birds but both he and his spouse Margaret made important collections of other vertebrates during a series of expeditions that continued until 1964. Although he died in 1965, he had already completed his contribution to the Handbook to New Guinea Birds (Rand and Gilliard, 1967), the first comprehensive guide to the identification of New Guinea birds.

The Third Archbold Expedition went to Dutch New Guinea (Brass, 1941). While, the Fourth Archbold Expedition (1953) focused on eastern New Guinea, including the Louisiade and d'Entrecasteaux archipelagos and Mt. Dayman at the eastern end of the Owen Stanley Range (Brass, 1956).

A little over a decade later the Commonwealth Scientific and Industrial Research Organization (CSIRO) of Australia expanded its regional land use survey program to New Guinea. This program, which continued in Papua New Guinea until 1976, resulted in the publication of 17 major reports (including three synthesis reports), several books and numerous papers covering most of SE Papua New Guinea, Bougainville, Buka, and parts of the highlands and the Sepik basin (see http://www.publish.csiro.au/?nid=289).

In 1961, J. Linsley Gressitt of the Bishop Museum established a field station at Wau and began an on-going series of major collecting expeditions throughout Papua New Guinea. The field station, which became the Wau Ecology Institute in 1972, went on to become an important site for scientific training and a major logistical base for Bishop Museum field expeditions to various parts of the country. Bishop Museum also collaborated with the Australian National University to construct a research station on the upper slopes of Mt. Wilhelm. Other Australian institutions, particularly the Australian Museum (Sydney) and South Australian Museum (Adelaide) also began biological field survey programs to various remote areas of the country.

As the biological knowledge of Papua New Guinea increased, so did concern for the conservation of its remarkable biota. In 1992 Conservation International and the PNG Department of Environment and Conservation, in collaboration with various museums, organized the Conservation Needs Assessment (CNA), a comprehensive effort to assess the distribution and diversity of the biota of the country. This resulted in the publication of a two-volume report treating all major taxonomic groups (Alcorn, 1993; Beehler, 1993). In addition the CNA identified all regions of the country with important biodiversity and as well as regions that were thought to be important but required further study. Shortly afterward, Conservation International, generally in collaboration with museums, began a Rapid Assessment Program (RAP) involving field surveys of putatively important biodiversity areas of the country. This program continued until around 2009, generally with one or two surveys per year (Alonso *et al.*, 2011).

During the past two decades biological field survey teams have reached many of the remaining unknown or poorly known parts of Papua New Guinea. This has resulted in the discovery of literally hundreds of new species, including more than 200 species of frogs and the deposition of thousands of specimens in museums in Papua New Guinea and overseas.

There are, for example, around 200,000 specimens of amphibians and reptiles from the Papuan region, mostly from Papua New Guinea, in museums around the world. A map of the various localities from which herpetological specimens have been collected and deposited in museums gives a rough idea on the areas of the country that have been surveyed (Figure 58). Although large parts of the country remain unsurveyed, such as large areas of Western Province and the Sepik Basin, survey teams have reached most of the major mountain ranges and lowland basins likely to be inhabited by restricted range species (Figure 59).

Figure 58. **Collecting sites of amphibians and reptiles in Papua New Guinea represented by specimens in museums**

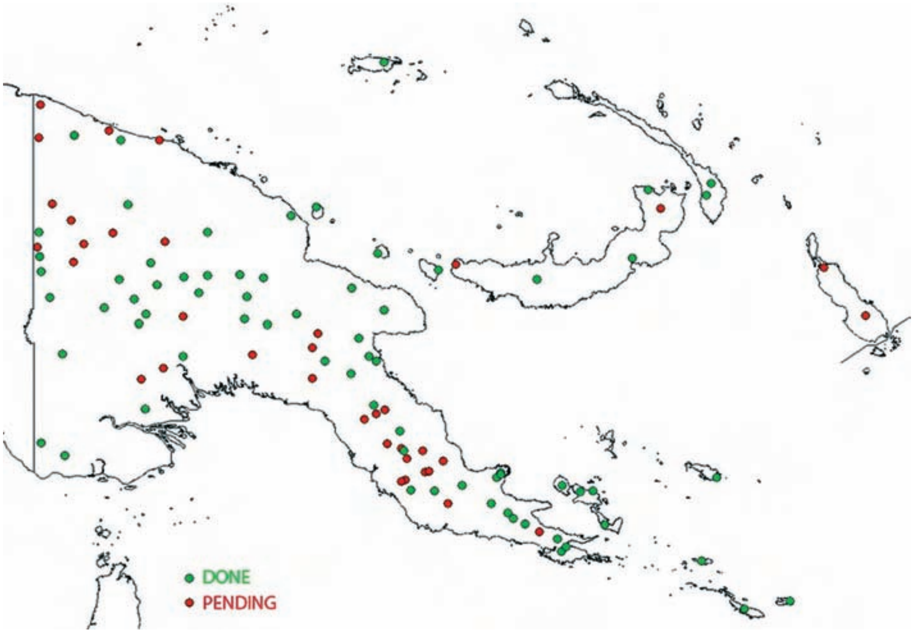


Figure 59. Field sites in Papua New Guinea that require surveys to document the herpetofauna of Papua New Guinea. Sites that have been surveyed are shown in green. Sites that require surveys are shown in red.

The specimens collected during field surveys and deposited in museums are crucial to the scientific naming of species and documenting their distributional occurrence. The rate at which species are discovered and described depends on the availability of specimens and the number of specialists working on that group. Groups that tend to have large geographic ranges and many workers, such as birds, tend to be discovered and named fairly quickly. Conversely, groups such as amphibians and reptiles, which have many restricted-range species and a relatively small number of workers, tend to take much longer to discover and describe.

Patterns of Distribution and Diversity

The ranges of all known species of terrestrial vertebrates have been mapped and are available as GIS shapefiles. We obtained the amphibian maps from the IUCN Red List website (http://www.iucnredlist.org/) and have prepared additional maps, using the same methodology, for all subsequently named species up to 31 March 2015. Similarly, we used reptile maps that we helped prepare at two IUCN Red List workshops, again updating the set to include all recently named species. The bird maps were obtained from BirdLife International and NatureServe (2014). We updated these to conform to all New Guinea species recognized by Pratt and Beehler (2014) and followed Dutson (2011) for the northern and southern Bismarck island arc taxa. We downloaded the mammal maps from the IUCN (2012) and 13 species range maps were digitized to include recently described species.

We derived maps of species richness using ArcGIS (v10.3). Papua New Guinea amphibians (all of which are frogs), reach their highest species density along the central mountains and in the mountains along the north coast (accreted terranes) (Figure 60). Species richness is lowest in the savanna regions of Western and Central provinces, which have pronounced dry seasons, and in the island provinces. Frogs, on account of their water permeable skin, cannot survive prolonged exposure to salt water and have difficulty reaching oceanic islands. This accounts for low species richness on Manus, Bougainville and the Bismarck islands.

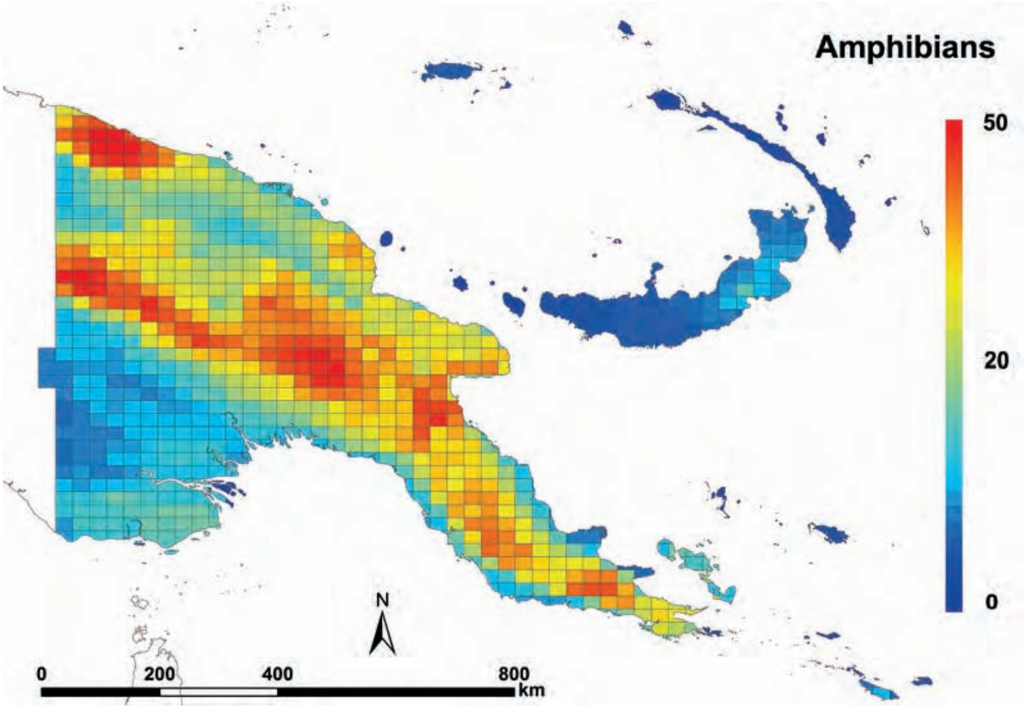


Figure 60. Species richness of Papua New Guinea amphibians by 25 x 25 km grid cell.

Although there are only four families of frogs inhabiting the island provinces of Papua New Guinea: Ceratobatrachidae, Microhylidae, Hylidae, and Ranidae, all represented on the island of New Guinea, the ceratobatrachids form the dominant anuran element in the islands with 43 of the 53 (81%) species. Ceratobatrachids are an ancient lineage of frogs that appears to be more adept than most frogs at crossing salt water gaps. The family is represented on Palau, the Philippines, north coast of New Guinea, Admiralty Bismarck and Solomon island chains, and Fiji.

Reptile species richness in PNG (Figure 61) is in many respects the inverse of frog species richness, with the highest concentrations of species in the savanna regions of Western and Central provinces and in coast regions, particularly along the north coast, including the Huon Peninsula.

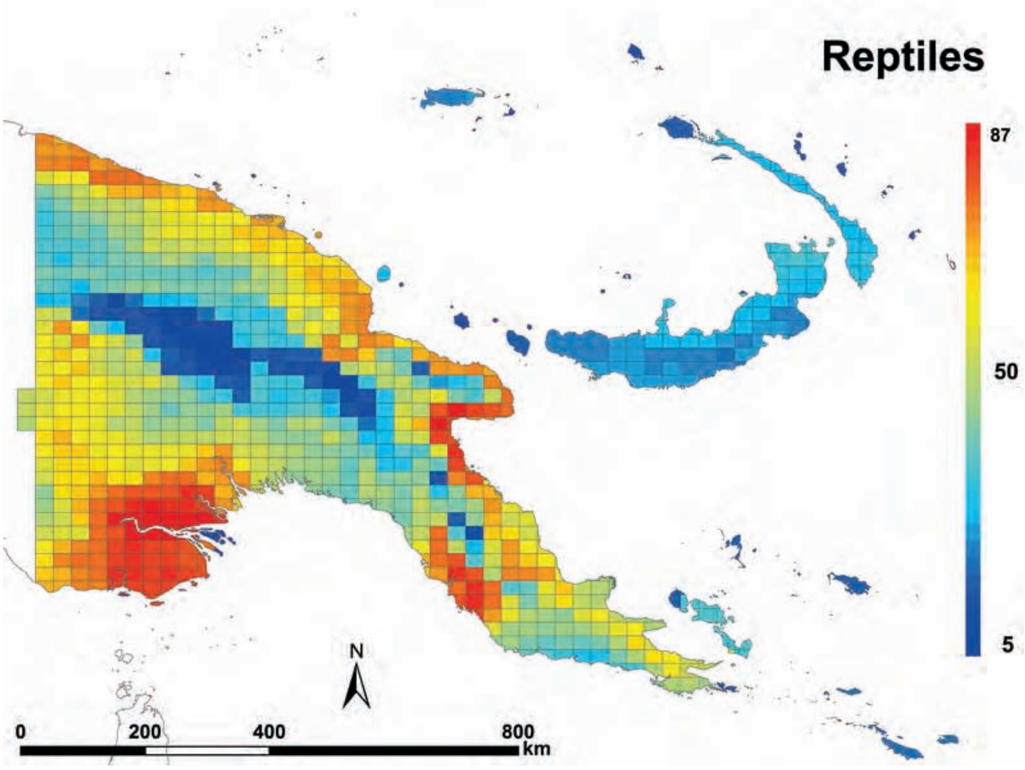


Figure 61. Species richness of Papua New Guinea reptiles by 25 x 25 km grid cell.

Reptiles tend of have much larger geographic distributions than do amphibians, and although there are slightly fewer reptile species (335) than amphibian (frog) species (342) known from Papua New Guinea, there is much greater overlap in the ranges of the various species and species richness reaches a high of 88 per 25 x 25 km grid cell (vs 52 for amphibians).

It is interesting to note that grid-cell totals for both amphibians and reptiles approach the totals for well-known study sites in the Amazon Basin. For example, Duellman (2005) found at Reserva Cusco Amazonico, in southern Amazonian Peru, a total of 66 species of anurans and 80 species of reptiles. Although Duellman's study site was considerably smaller (~6 km^2) than a 25 x 25 km grid cell (625 km^2), he sampled a wide range of representative microhabitats. In as much as many Amazonian amphibians and reptiles have large geographic ranges, it is likely that the same basic assemblage of species would occupy a much larger area and the Papua New Guinea and Amazonian totals are roughly comparable.

However, the grid cells with the highest amphibian species richness in Papua New Guinea tend to be in places such as the Bewani Mountains in West Sepik Province that include a mix of lowland, hill forest and montane elements. If we restrict comparisons strictly to lowland rain forest, such as Utai at the foot of the Bewani Mts, which has one of the richest assemblages of amphibian and reptile species in Papua New Guinea, there are around 30 species of frogs, 30 species of lizards and fifteen species of snakes (Austin *et al.*, 2008). Comparable totals for Cusco Amazonico are 66 species of frogs, 25 species of lizards, 51 species of snakes.

Totals for Borneo are similar to the Amazon. For example, at the Danum Valley Research Centre there are 53 species of frogs (Sheridan *et al.*, 2012), 32 species of lizards (Anonymous, 1993; Das and Lim, 2003), and 36 species of snakes (Murphy *et al.*, 1994).

These comparisons suggest that alpha – or within habitat – diversity in Papua New Guinea is low compared to Borneo and the Amazon but overall diversity, gamma, is obviously high, suggesting that between habitat diversity, beta, is also high.

The birds (Figure 62) show a very different pattern to the reptiles. Species richness is high throughout the south-eastern peninsula of Papua New Guinea and along the slopes of the central mountains. This is a rather surprising pattern that may, in part, be an artefact. Because the southeast peninsula is much narrower than central and western Papua New Guinea, it is likely that the grid cells on the southeast peninsula contain greater mix of altitudinal zones than do the grid cells in central and western regions of the country. This would tend to inflate species richness. Although bird species richness tends to peak in the lowlands (Beehler, 1982), most lowland species range up to at least 500 m elevation. These species tend to drop out at higher elevations or are replaced by montane congeners; overall richness tends to decline with higher elevation (Diamond, 1973). It is likely that grid cells that include the lower slopes of mountains contain a mix of lowland and montane species and therefore have the highest grid cell richness, as is clear in the Central Highlands. As discussed earlier, the decline in richness with elevation is probably masked in the SE peninsula.

Interestingly, although bird richness on the southeast peninsula is unquestionably high, endemism is low. There are only four species of birds that are endemic to the southeast peninsula: Brown-headed Paradise-Kingfisher (*Tanysiptera danae*), Streaked Bowerbird (*Amblyornis subalaris*), Eastern Parotia (*Parotia helenae*) and Eastern Alpine Mannikin (*Lonchura monticola*).

Mammal species richness is similar to that for birds with highest richness along mountain slopes (Figure 63).

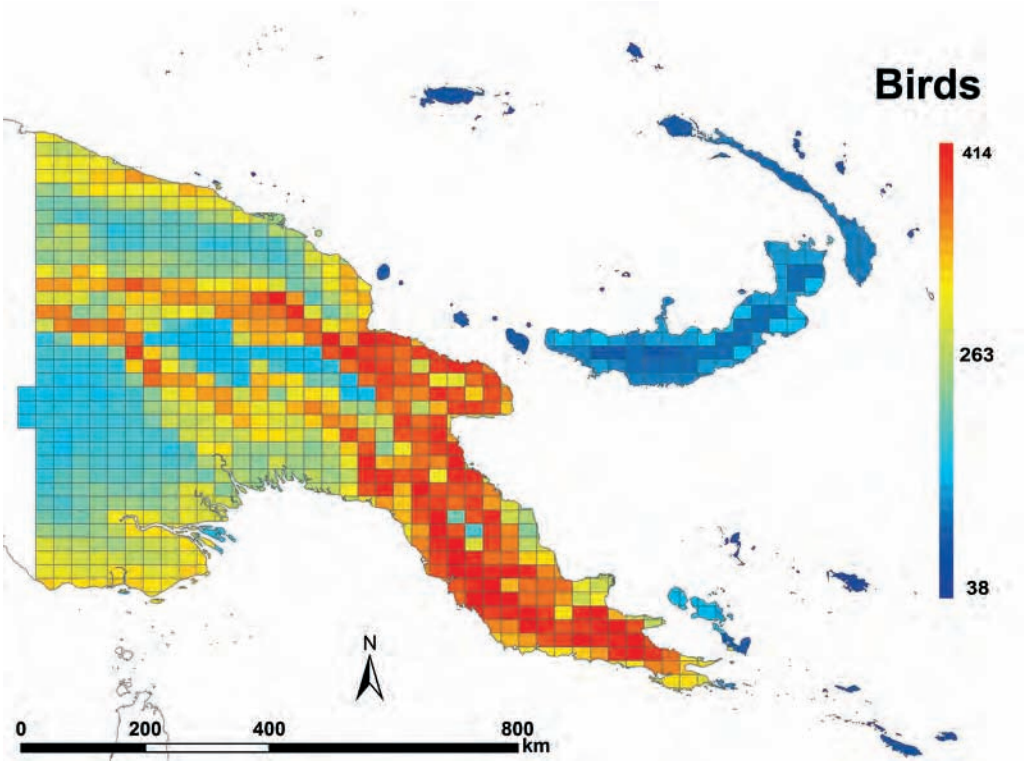


Figure 62. Species richness of Papua New Guinea birds 25 x 25 km grid cell.

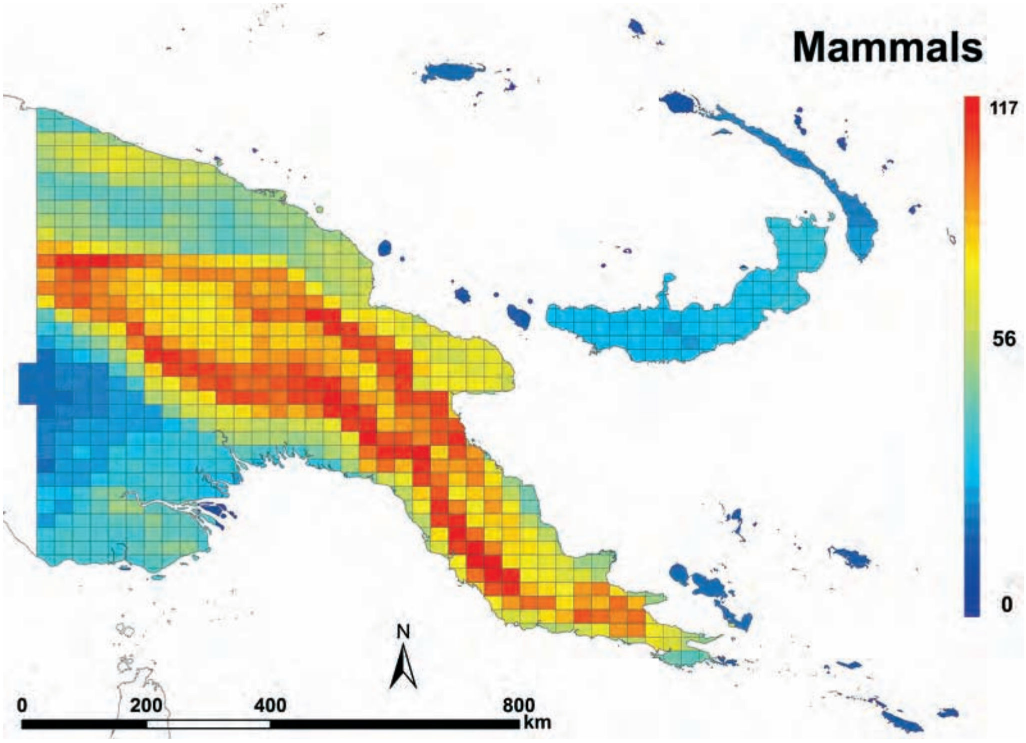


Figure 63. Species richness of Papua New Guinea mammals by 25 x 25 km grid cell

Endemism

The Papuan region has a complex tectonic history (Pigram and Davies, 1987; Allison, 2009) and this has strongly influenced the distribution of the biota (Allison, 1996; 2009). A number of different zoogeographic schemes have been proposed to describe the distribution of the fauna. See, for example. Polhemus and Allen (2007) for the freshwater biota, Allison (2007a) for amphibians and reptiles, Pratt and Beehler (2014) for birds and Flannery (1995) for mammals. Shearman and Bryan (2010) used a bioregional scheme – based on biogeography and climate – to document patterns of rain forest cover, deforestation and forest degradation in Papua New Guinea. For consistency we have followed their scheme, the location of each bioregion can be found in Annex2.

The geographic ranges of most species of Papua New Guinea vertebrates are not accurately known. The range maps therefore represent approximations based on all available data and expert opinion. This commonly results in maps that likely exaggerate the actual range of the species. Because this can obscure patterns of endemism, we consider a species to be endemic to a bioregion if 90% or more of its range is within that bioregion.

The bioregion with the highest level of amphibian endemism is the Central Highlands, followed by the Owen Stanley Ranges and Sepik-Markham bioregions (Figure 64). This pattern tends to mirror species richness (Figure 60). These bioregions, which are dominated by uplands, clearly represent major centres of diversification for the amphibians in Papua New Guinea.

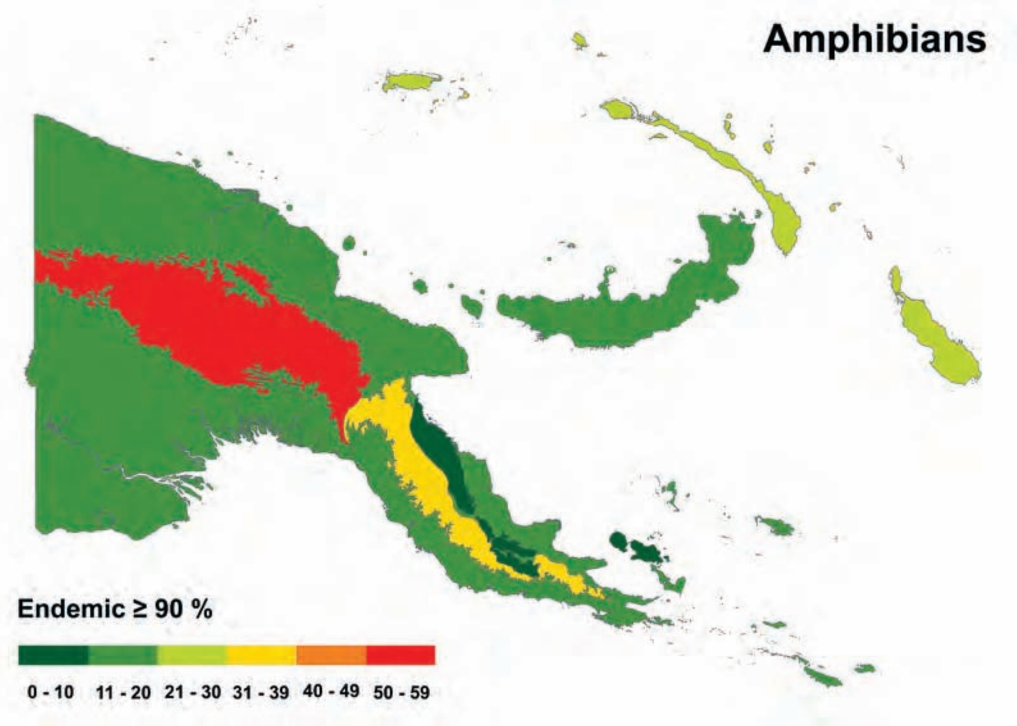


Figure 64. Amphibian endemism in Papua New Guinea by bioregion (based on scheme proposed by Shearman and Bryan, 2010).

Reptile endemism is highest in the offshore islands and peaking in the South Eastern Islands and North Bismarck bioregions (Figure 65), with many species of lizards endemic to the individual islands. The birds show a similar pattern and reach their highest levels of endemism in the North Bismarck Bioregion (Figure 66).

Mammal endemism is highest in the Central Highlands Bioregion (Figure 67) and to a lesser degree in the Sepik-Markham and Northern Bismarck bioregions. This latter bioregion, because of the presence of many single-island endemics, has the highest overall level of endemism (Figure 68).

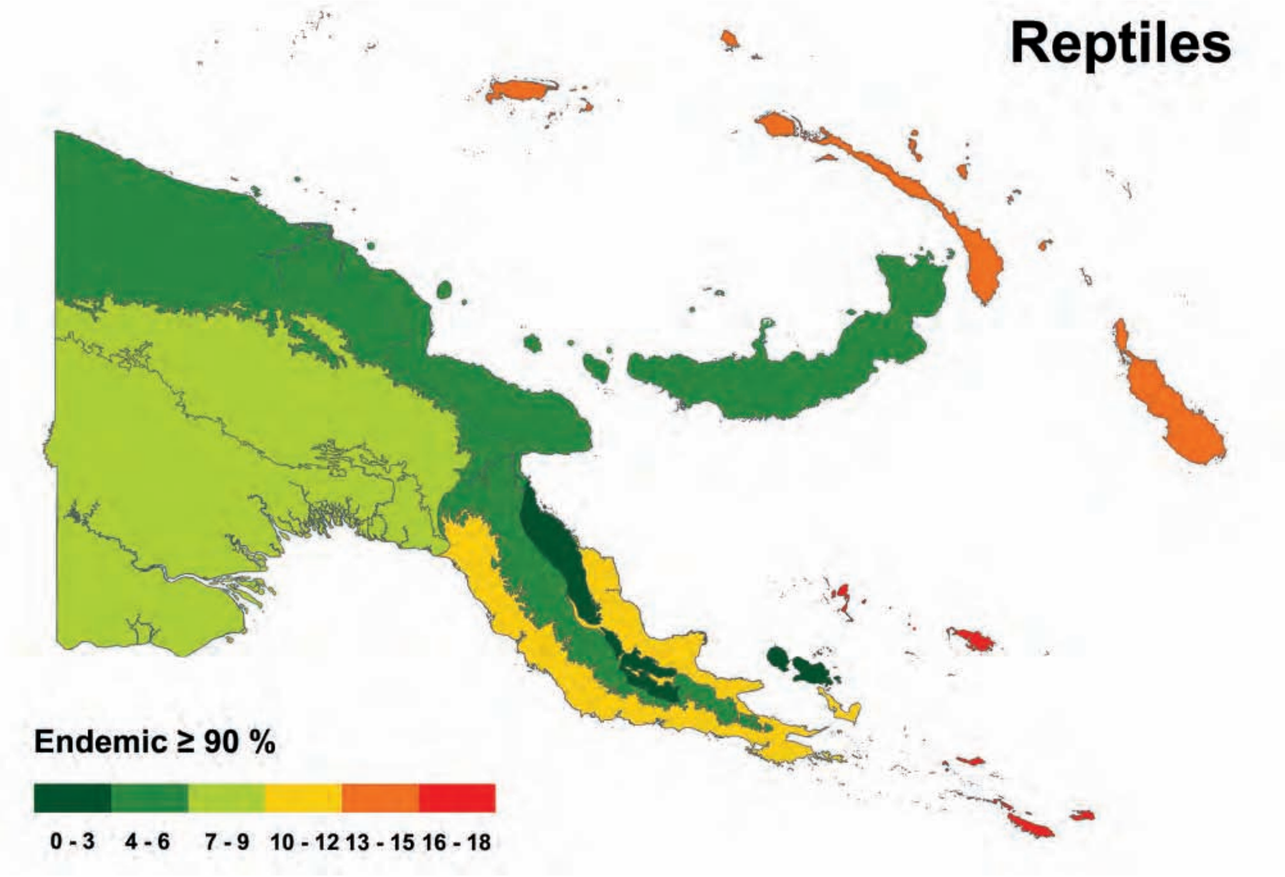


Figure 65. Reptile endemism in Papua New Guinea by bioregion (based on scheme proposed by Shearman and Bryan, 2010).

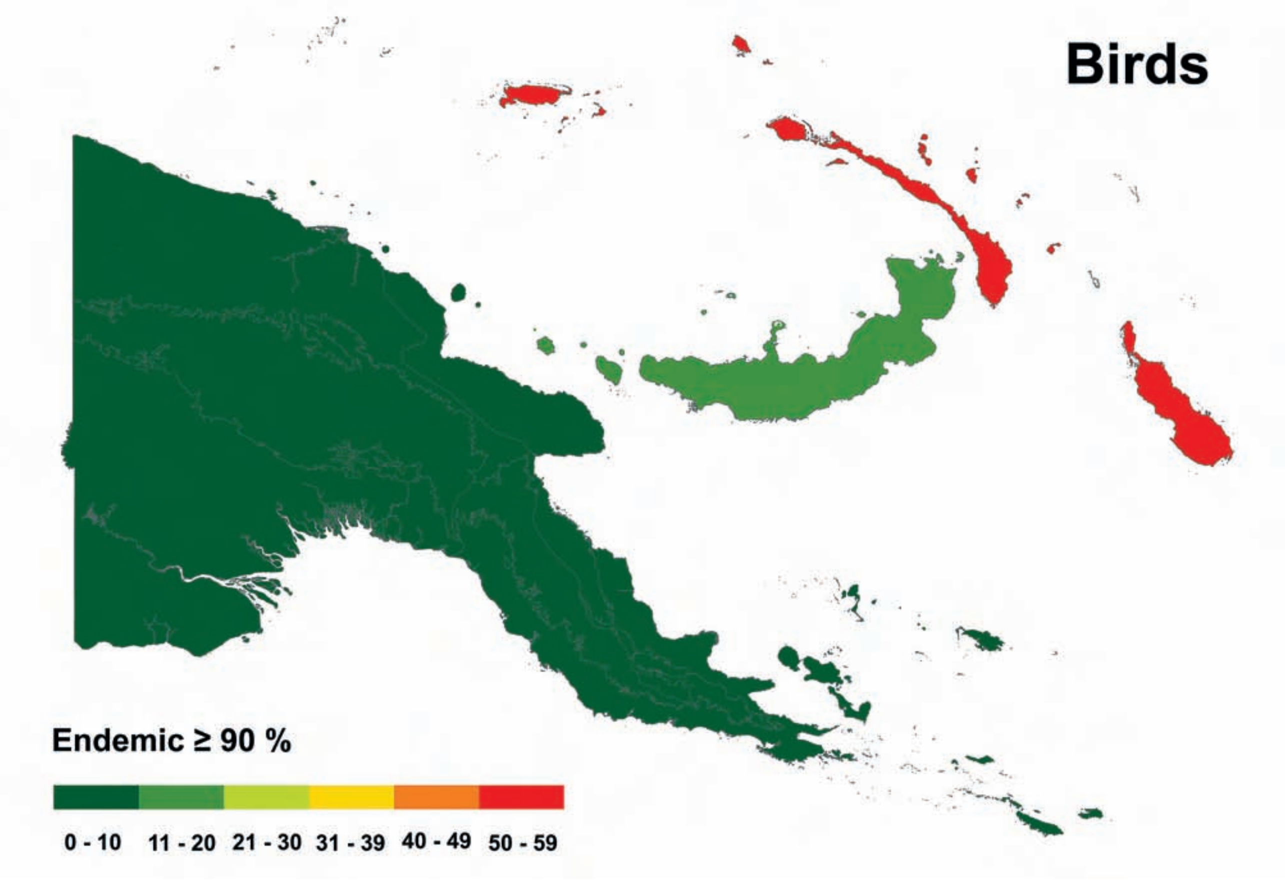


Figure 66. Bird endemism in Papua New Guinea by bioregion (based on scheme proposed by Shearman and Bryan, 2010).

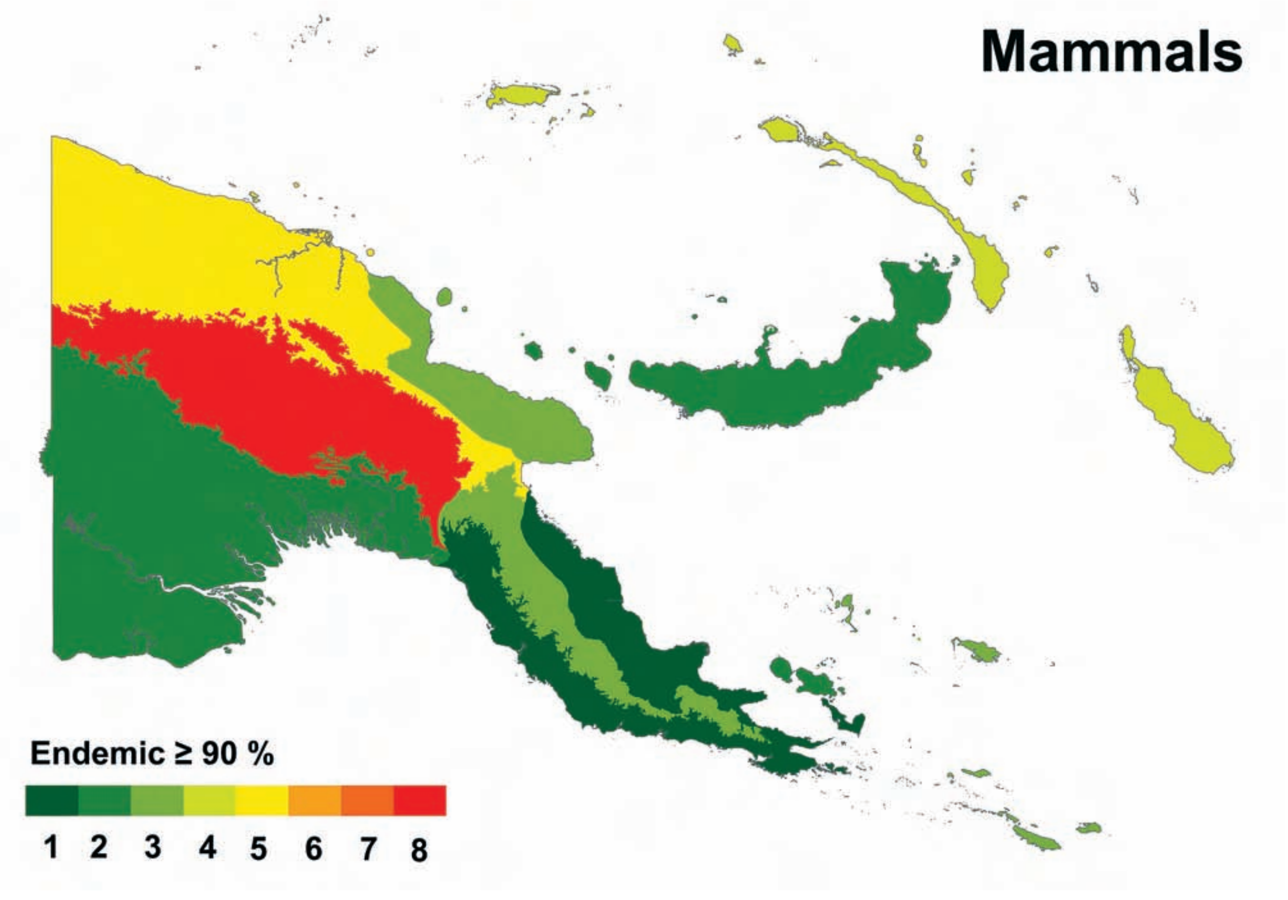


Figure 67. Mammal endemism in Papua New Guinea by bioregion (based on scheme proposed by Shearman and Bryan, 2010).

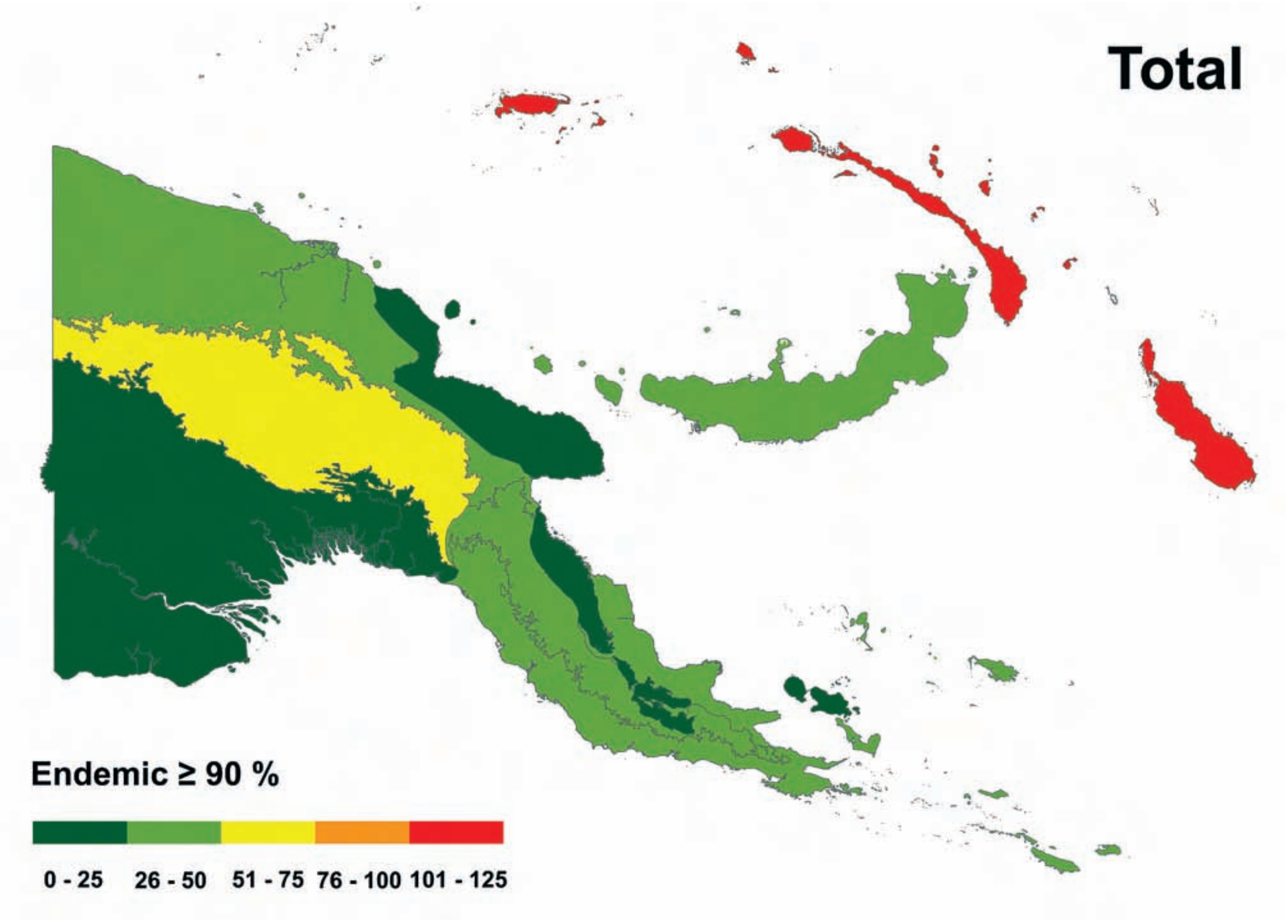


Figure 68. Overall terrestrial vertebrate endemism in Papua New Guinea by bioregion (based on scheme proposed by Shearman and Bryan, 2010).

Impact of forest Loss on the Vertebrate Biota

The forest change assessment undertaken in Chapter 1 found that deforestation and forest degradation differed across PNG's bioregions (Figure 69 - Figure 70). Rain forest loss between 2002 and 2014 was greatest in the Southern Bismarck (New Britain) Region, followed by the Sepik-Markham, Fly-Gulf, and the Northern Bismarck (Manus, New Hanover, New Ireland and Bougainville) regions, all of which had rates of rain forest loss that exceed the 2002-2014 average for PNG of slightly more than 4%. Most of this loss was concentrated in the lowlands (Figure 70), particularly in the Adelbert Mountains and the Sepik Basin (Figure 69).

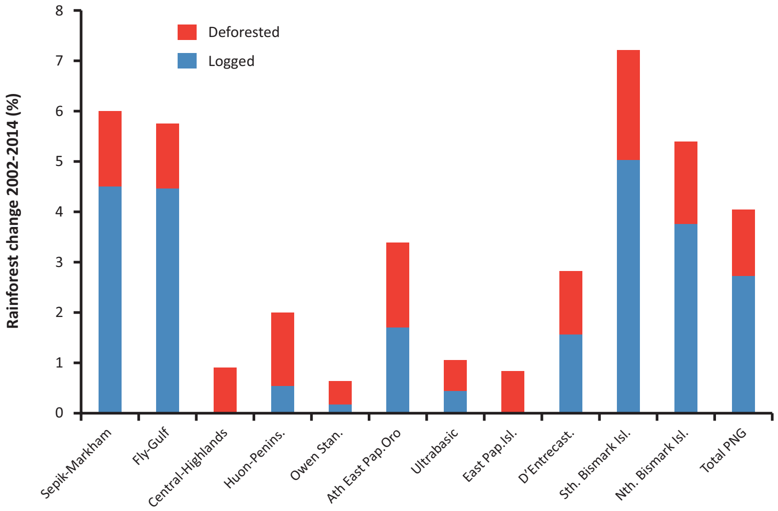


Figure 69. **Rainforest change (deforestation and forest degradation through logging) 2002-2014 (%) in PNG's bioregions.**

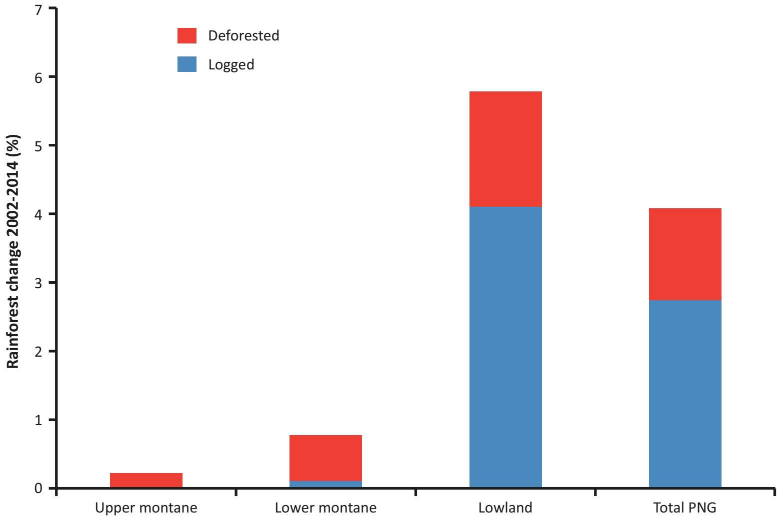


Figure 70. **Rainforest change (deforestation and forest degradation through logging) 2002-2014 (%) in PNG's altitudinal zones.**

Rain forest loss was also reasonably high in the extensive lowland basins north and south of the main ranges in western Papua New Guinea and throughout the islands region. It was lowest in the mountains, particularly in the Owen Stanley Range.

Most of the vertebrate biota is found in rainforest, so any loss of that habitat can potentially cause the loss of species. In order to evaluate this, we examine patterns of species richness and restricted-range endemism in relation to forest loss.

Although our knowledge of the vertebrate biota of PNG has increased markedly during the past several decades, some groups, particularly amphibians and reptiles, remain poorly known. And even the best known group, birds, are subject to on-going taxonomic revisions that can radically change species range maps and alter apparent patterns of overall distribution and diversity. Our analysis is necessarily course and focused on whether areas with the highest rates of forest loss correspond to areas of high species richness and restricted-range endemism.

Amphibian richness is highest in the mountains and is particularly high in the Bewani Mountains, an accreted terrane in the north western corner of the country (Figure 60). These same areas are also high in restricted-ranged endemic species, although pockets of these are scattered around the country (Allison and Tallowin, in prep.). The relatively high rate of forest loss in the North Coast Ranges potentially threatens a large number of frog species endemic to that region. Although forest loss in the Admiralty and Bismarck archipelagos and on Bougainville is relatively high, the number of frogs inhabiting this this region is relatively low. Many of these frogs are island endemics, but they tend to be widely distributed throughout the islands that they inhabit.

Reptile richness tends to peak in the coastal regions where rain forest loss is highest (Figure 61). Restricted-range endemism (lowest 10th quantile of range size) is highest in the islands of Milne Bay and in the mixture of savanna, sclerophyll and hill forests at the base of the Owen Stanley Mountains near Port Moresby. There are also pockets of restricted-range endemics in the North Coast Ranges, a region with high rates of forest loss.

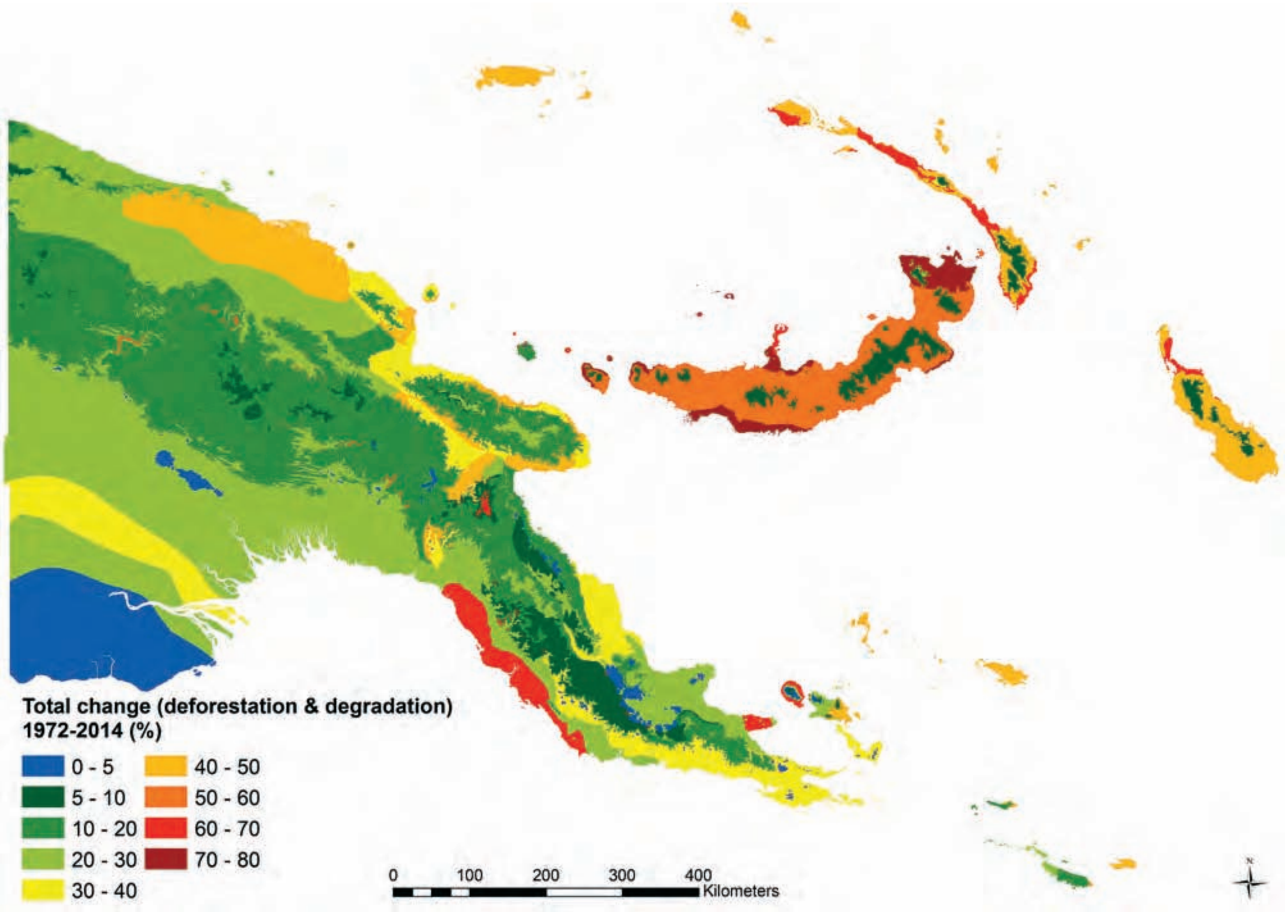


Figure 71. Rainforest change (deforestation and forest degradation) 2002-2014 in Papua New Guinea's bioclimatic regions.

The impacts of forest loss on reptile populations are difficult to evaluate. Many species of reptiles, particularly lizards, tend to have relatively large geographic ranges and are found mainly at the forest edge, in clearings or second growth, so their populations may be relatively unaffected by localized forest loss.

Bird species richness is highest in the rain forest throughout the country and appears to peak in the hill forest regions (Figure 62). Most mainland New Guinea bird species have relatively large geographic ranges and therefore endemism in these bioregions tends to be low. However, island endemism is high, with concentrations of restricted range endemics confined to the Bismarck bioregions and Bougainville where forest loss is high. Although most of the bird species endemic to this region occur in rainforest, they are not confined to this habitat and many of them have adapted to second growth or occur in montane regions that are currently unaffected by rain forest loss (Allison and Tallowin, in prep.). Nevertheless, it is clear that continuing forest loss in the Islands Region and its potential impact on the rich array of endemic birds that occur there is a matter of urgent conservation concern (Dutson, 2011).

Mammal species richness is similar to that of reptiles and birds but centred primarily in the mid-montane regions north and south of the main ranges (Figure 63). The highest concentration of restricted-range species is in the mountains of West Sepik Province, particularly the Torricelli Mountains on the North Coast and the Star Mountains adjacent to the Indonesian border.

Large areas of West Sepik Province and adjacent parts of the central Highlands were burned during the El Niño event of 1997-1998. This, together with over-hunting are thought to have caused significant declines in some of the mammal species, particularly several species of tree kangaroos, largely confined to this region.

Conservation Status of the Vertebrate Biota

According to the IUCN Redlist (2015), 11 species of amphibian face an increased risk of extinction. It is likely however, that only one species of Papua New Guinea frog is truly endangered (Allison, 2014). This species *Choerophryne siegfriedi* (formerly Albericus) is endemic to Mt. Elimbari in Chimbu Province and is considered to be Critically Endangered due to forest loss throughout its small range.

There are currently seven species of threatened Papua New Guinea reptiles (IUCN Red List, 2014) with an additional species identified during a recent IUCN Redlist workshop (2014). Six of these species are turtles, with two taxa, *Chelodina pritchardi* and *Pelochelys signifera*, considered to be Endangered and the rest list as Vulnerable. In addition a snake endemic to Bougainville and the Solomon Islands, *Loveridgelaps elapoides*, and a gecko from Western Province, *Cytrodactylus derongo*, are also listed as Vulnerable.

Deforestation is unlikely to have a significant impact on the turtle species which are primarily at risk due to over-harvesting for human consumption and the pet trade. Although the snake and gecko species may be locally affected by deforestation, further research is required to elucidate their true distribution and to accurately assess the effect of this threat on their population.

A total of 39 species of birds are threatened in Papua New Guinea, of which, 34 are considered to be Vulnerable, four as Endangered and one as Critically Endangered.

In general those species listed as Vulnerable are still represented by reasonably large populations in Papua New Guinea but some, such as two species of cassowaries (*Casuarius casuarius* and *C. unappendiculatus*) inhabiting the lowlands of the south and north coasts, respectively, together with the Vulturine Parrot (*Psittrichas fulgidus*) and several species of pigeons, are threatened by over-hunting and have been extirpated from many areas of the country. The rest of the species regarded as Vulnerable include taxa that are uncommon to rare, occupy a small geographic ranges or are migratory species impacted by the loss of breeding habitat elsewhere.

The four species that are thought to be endangered include *Otidiphaps insularis* (regarded as a subspecies of *O. nobilis* by Pratt and Beehler, 2014), *Pitta superba, Actenoides bougainvillei* and *Aplonis brunneicapillus*.

The *Otidiphaps* is restricted to Fergusson Island in the D'Entrecasteaux group (Milne Bay Province). There are no recent sightings (Pratt and Beehler, 2014). Forest loss in the D'Entrecasteaux group is around 3.5% and is particularly concentrated in the lowlands of Fergusson Island, so the continuing loss of forest there is a matter of high conservation concern.

Pitta superba is restricted to Manus and was historically widespread, but there are few recent sightings (Dutson, 2011). Forest loss on Manus is high and is likely to endanger this species. *Actenoides bougainvillea* is a kingfisher from the Solomon Islands variously classified as a Bougainville endemic or also occurring on Guadalcanal (Dutson, 2011). It is a little known montane species that may be threatened by logging.

Aplonis brunneicapillus is a starling endemic to Bougainville and several other islands in the Solomons group, including Choiseul, Rendova and Guadacanal. It is thought to be threatened by habitat loss (Dutson, 2011).

The single critically endangered bird species is a seabird, *Pseudobulweria becki*, known from the Papua New Guinea – Solomon Islands area. Dutson (2011) reports it was originally known only from two specimens collected in the 1920s but is now known to be locally common in the seas between New Britain and New Ireland and may breed in the Hans Meyer Range of New Ireland.

There are 12 species of Papua New Guinea mammals listed as Vulnerable on the IUCN Red List. These are a mix of relatively widespread but uncommon species and narrow-range endemics.

There are nine species of endangered marsupials, including two species of wallabies (*Thylogale lanatus* and *T. calabyi*), the Woodlark cuscus (*Phalanger lullulae*) two species of bandicoots (*Echymipera davidi* and *Peroryctes broadbenti*), three species of tree kangaroos (*Dendrolagus notatus, D. matschiei* and *D. goodfellowi*), a triok (*Dactylopsila tatei*), four species of rodents (*Paramelomys gressitti, Paraleptomys rufilatus, Melomys matambuai, Solomys salebrosus*), and the Bougainville monkey-faced bat (*Pteralopex anceps*).

The Critically Endangered species include a monotreme, the Eastern long-beaked echidna (*Zaglossus bartoni*), six species of marsupials, including two cuscuses (*Spilocuscus rufoniger* and *Phalanger matanim*), the Northern glider (*Petaurus abidi*), the Black dorcopsis (*Dorcopsis atrata*), two species of tree kangaroos (*Dendrolagus scottae* and *D. pulcherrimus*), Poncelet's giant rat (*Solomys ponceleti*) and three species of bats (*Pharotis imogene, Aproteles bulmerae* and *Pteralopex flanneryi*).

Marsupials comprise about half the assemblage of Endangered and Critically Endangered mammals. Because many of them are relatively large, they are important sources of bush meat and threatened with over-hunting in many areas. Although the overall loss of forest is relatively low in the Central Highlands bioregion, a hot spot for restricted range mammals, much of this loss of forests is concentrated in the northwestern part of the bioregion that is especially high in restricted-range endemics. The combined effects of forest loss and over-hunting has already caused the localized extinction of relatively widespread species such as the eastern long-beaked echidna, (*Zaglossus bartoni*) and Goodfellow's tree kangaroo (*Dendrolagus goodfellowi*) and may very well lead to the extinction of some of the restricted-range species. Similarly, loss of habitat and hunting pressure have extirpated many populations of large rodents (*Solomys salebrosus* and *S.ponceleti*) in the Bismarck bioregions, threatening these species with extinction.

Chapter 6

State of the orchids in PNG's forests

E.F. de Vogel

Ed de Vogel is an orchid specialist with 35 years of experience in orchid taxonomy and who has spent 8 years working in the forests of Southeast Asia. His experience in New Guinea comprises 3 months field work in Papua, Indonesia, and 2.5 years field work in PNG. He has collected 10,000 herbarium specimens and 15,000 cuttings of live orchids for sister institutes in Southeast Asia and both the National Herbarium Nederland and Hortus botanicus Leiden. He is coordinator and co-author of the project "Flora Malesiana: Orchids of New Guinea", which described all accepted 2716 species of orchids of New Guinea on 6 CD-ROMs, illustrated by c. 16000 pictures, maps, and type images. Retired in 2004, he continues his New Guinean orchid work as honorary researcher in Naturalis Biodiversity Center and Hortus Botanicus Leiden in The Netherlands.

Orchids are an ancient plant family which originated more than 80-90 million years ago, living together with Dinosaurs in the Cretaceous. Orchids split off as the first branch of the Asparagus group, to which belong, among others, irises, onions, hyacinths, daffodils, agaves and asparagus. Biological clock calculations on a 20 million year old fossil bee with an orchid pollinarium, found included in amber, lead to an age of around 80 million years.

Over the centuries orchid flowers have been rated as exotic, rare, vulgar, expensive and mysterious, long-lasting, big and very showy, and able to evoke romance and passion. This idea about orchids is so widespread, that regularly visitors to Botanical Gardens ask "Where are the orchids?" while they are standing in a glasshouse crammed to the roof with them. In reality, 90% of orchids have tiny flowers which last only a short period. Many are rarely recognised as orchids, they are very common, and nobody would spend a toea on them. With perhaps as many as 30,000 species, orchids are the largest plant family in the world. They are found worldwide except within the polar circles, and have their most extensive diversification in the tropics. They grow from sea level to near the eternal snow limit on mountains. In tropical mountain ranges the zone richest in orchid species is between 1,000 and 2,500 m. Three quarters of all orchid species are epiphytes, that is, they grow on trees but are not direct parasites, and one quarter are terrestrial.

What is an orchid? A very technical detail inside the flower determines that. The style of the ovary is fused with the filament(s) of the anther(s) and this structure is transformed in shape, thus forming a so-called column which carries both the stigma (usually as a concavity) and the anther(s). Most orchids have 1 anther (2 or 3 in a few orchid groups). Presence of a lip (this is one of the petals which is transformed in a special, often ornamented organ), resupination of the flower (turning it upside down so the lip is below), pollinaria (pollen packages) for distributing all pollen in one go, and parallel nerved leaves are very common, but these characters do not occur in all species, and are also found in other plant families. Common pollinators of orchids are bees, wasps, flies, butterflies, moths, and honey eating birds.

What is currently known about PNG orchids?

More than a century of knowledge has been accumulated about PNG orchids. As early as 1911-1914, the German Rudolf Schlechter described and illustrated more that 1100 new PNG orchid species in his work “Die Orchidaceen Deutsch Neu Guineas” [The Orchids of German New Guinea] and other publications. For adjacent former Dutch New Guinea (now Papua, Indonesia), J.J. Smith did the same for another 530 species. Both published their descriptions in Latin. Subsequently many hundreds of new species were described, usually as solitary descriptions, not in the context of a treatment of a whole group of related species. That means that species were often described two or more times, and among species that are variable in appearance the number of these so-called synonyms can be quite large. The common species *Pholidota imbricata* which ranges from the Himalaya to deep in the Pacific has 11 synonyms at species level and 5 at variety level, now all considered to belong to one species. The last decades several group revisions were made for New Guinea orchids, most in the genus Dendrobium.

The project “Flora Malesiana. Orchids of New Guinea” (1996-2010) published a checklist of all 2716 species that were recognised on the island at that time, and provided for each species a description, illustrations, photographs, a distribution map and further details in the English language, on 6 CD-ROMs, thus providing a synopsis of all available information, supplemented with the authors’ own observations and revision work. At the Naturalis Biodiversity Center in The Netherlands, the CD series is now being converted to a website, and will soon be free to use by everyone; this website contains almost 16,000 illustrations. Since publication of those CDs another 150 new species have been published, and another few hundred plants have been collected which are suspected to be undescribed. An update of the contents with those 150 species and thousands of new photographs is planned to be ready in 2 or 3 years time.

Orchid diversity

Orchids are subdivided into 5 subfamilies, all with representatives in New Guinea. The Apostasia subfamily (2 genera, 18 species) is present with 2 widespread species: *Apostasia wallichii* and *Neuwiedia veratrifolia*. The Vanilla subfamily (15 genera, c. 240 species) has 5 genera on the island with about a dozen species; the best known genus is Vanilla, but the PNG species do not produce the famous flavour spice which is the second most expensive in the world after saffron. The Cypripedium subfamily (5 genera, c. 170 species) has 1 genus in New Guinea, Paphiopedilum, with 4 endemic species; these are the famous Slipper Orchids which are highly valued in horticulture. The Orchid subfamily (250 genera, c. 4,700 species) is present with 31 genera and c. 200 species; mostly ground orchids with soft, convolute young leaves. By far the largest is the Epidenrum subfamily (550 genera, c. 20,000 species), with 93 genera and maybe some 2700 species in New Guinea. Here belong the mega genera Bulbophyllym (636 species, with dozens more to come), and Dendrobium (560 species, also far from complete).

What knowledge is lacking?

The number of around 3000 species recorded for the island New Guinea is bound to change. Most genera are composed of species which have never been critically compared, and it is anticipated that many names represent synonyms. This can reduce the number of recognised species considerably. On the other hand, from more than half the surface of New Guinea not even one orchid has been collected and documented within a mile’s radius. And during past expeditions the only orchids collected were those that were in flower, while the non-flowering ones were left in the field and remained unrecorded. It is common that at a given time and place usually less than 10% of all species present in that area are flowering. That means that this way more than 90% of the species are missed. The project “Flora Malesiana. Orchids of New Guinea” of the National Herbarium The Netherlands, in cooperation with the National Capital Botanic Gardens (NCBG) Port Moresby, and later PNG Forest Reseach Institute (PNG FRI), collected in a few dozen localities live plants of all different vegetative forms recognised, and these were grown to flowering in the NCBG Port Moresby and in the Hortus botanicus Leiden, The Netherlands. There up to 60% of all species finally flowered and were collected, photographed and documented, producing a wealth of new information about distribution of commoner species, and in this way also undescribed species were detected. Experience from the Flora Malesiana (FM) project learns that from any mountain with undisturbed vegetation easily 25 or more undescribed species can be collected, and from undisturbed lowland forest 10 or more. This can boost the number of actual species considerably. This author estimates that the discovery of new species will exceed the reduction of names due to duplicate naming of the same species by a factor 3-4. Already a few hundred suspected new species have turned up during fieldwork in the last decades, which will be described in due time. In addition, among the unnamed specimens in Herbaria many dozens of undescribed species are to be found.

An example of the incomplete knowledge about occurrence of orchids in Papua New Guinea has been worked out for New Britain. In literature and databases 114 species are recorded from all over this island. The Flora Malesiana project collected there in only 3 weeks time in 3 lowland areas a total of 122 species; these include 83 identified species, at least 32 identified to genus of which at least 5 are undescribed, plus 7 of the 114 described species. Only 45 species including those 7 are duplicated in both literature and the FM collections. The FM activities thus bring the total number of orchids recorded for New Britain at 191. From the island there are many dozens of species in the Leiden Hortus which are still alive but have not flowered so far, among these there are most probably still quite a few undescribed species as well.

Endemism

A flora is more unique when the proportion of its endemic species is larger. Endemic species occur only in a restricted area. In this respect New Guinea ranks among the areas with the highest endemism in the world. More than 90% of the orchids in New Guinea occur only on this island. Compared to other island groups in the region: The Philippines have 74%, Borneo 55%, Sumatra 41% and Java only 31% endemism.

The uniqueness of a region is in addition determined by the number of species per surface area. Create a diagram (Figure 72) plotting the area on the horizontal axis, and the number of species on the vertical axis, and insert the data of all the island groups in the Malesian area except New Guinea in the diagram. When the line is drawn symbolising the increase of species with enlargement of the area, a nice parabolic graph appears. Then plot New Guinea in the diagram, and it appears that it falls entirely outside the range for the other regions. In fact the number of species is more than twice as high as would be expected from the graph. Also in this aspect New Guinea is unique in the region.

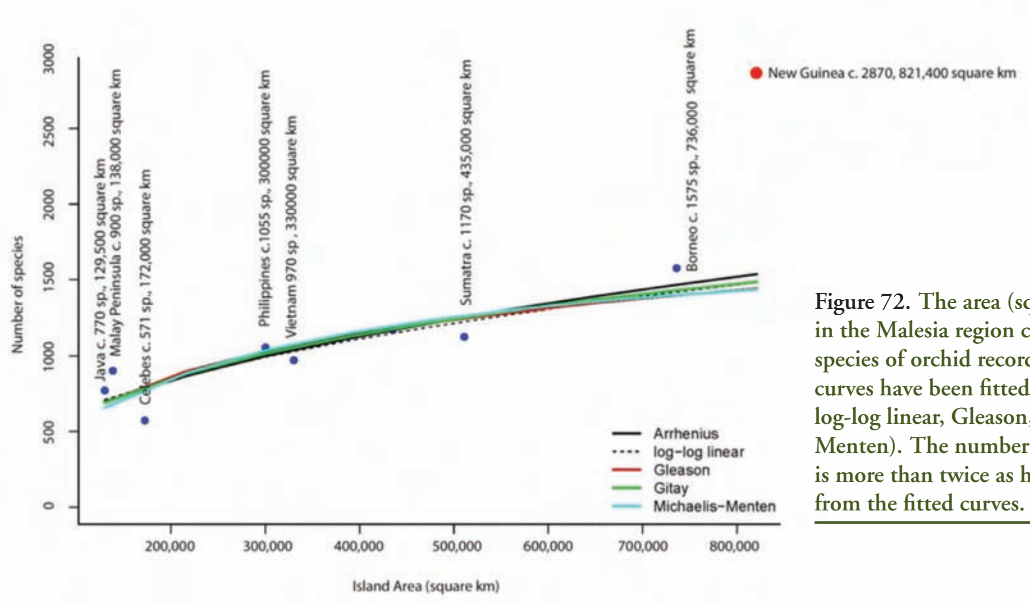


Figure 72. The area (square kilometres) of islands in the Malesia region compared to the number of species of orchid recorded in each island. Three curves have been fitted to the data (Arrhenius, log-log linear, Gleason, Gitay, and Michaelis-Menten). The number of species in New Guinea is more than twice as high as would be expected from the fitted curves.

Habitat requirements

Terrestrial orchids

About a quarter of all orchid species grow terrestrially. They can grow with their roots in mineral soil, or among litter or in moss cushions. Some produce pseudobulbs which contain a food supply, which usually serves as a means to survive during a rest period. That can be in a dry season, or after flowering and fruit setting. Others do not have tubers but have a creeping stem base and roots which remain hidden in the litter. And there are types which develop a swollen stem base which stores food and water. Most of these orchids have (sometimes partially) green leaves with chlorophyll, and are autotrophic plants which are capable of photosynthesis, although they also have a mycorrhiza, a symbiotic association between fungus hyphens and orchid roots. The fungus hyphens are tolerated in the roots and the rhizome and the basal part of the stem. Where they penetrate further into the orchid, the hyphens are dissolved by the cells they enter, and the orchid utilises the remains as nutrients. Terrestrial orchids range in size from quite small to large; some are large climbers, like *Dipodium* and *Vanilla*.

Holomycotrophic plants, formerly named saprophytes, lack chlorophyl, and are incapable of photosynthesis; they obtain all nutrients, carbon and minerals, from fungi which decompose decaying organic matter. These are mostly inconspicuous dull-coloured plants (whitish, yellowish or brownish) with reduced leaves, only some are large climbers, like *Pseudovanilla* and *Galeola*.

Epiphytic orchids

Epiphytic orchids grow on host plants like trees and shrubs, but do not obtain nutrients directly from their host; they are not direct parasites on the host plant. That is, they depend on mycorrhiza which parasitise on the host, like the terrestrial orchids. Epiphytes are autotrophic plants capable of photosynthesis.

A distinction can be made between humus epiphytes and bark and twig epiphytes, which have a different strategy to obtain mineral nutrients. Humus epiphytes accumulate litter which decomposes into humus, the fungus decomposes this organic matter, the orchid breaks down the hyphens and obtains its nutrients. With bark and twig epiphytes the hyphens penetrate the bark of the host plant, enter the living cells, and dissolve the contents. The orchid profits from the fungus as explained.

Another distinction is in plants with pseudobulbs (swollen stem parts), and plants without. Pseudobulbs are storage organs which contain water and nutrients; plants with pseudobulbs often have a sympodial growth, each stem has a limited growth, a new shoot will develop from a bud lower on the existing stem. Plants without pseudobulbs, mainly the monopodial orchids which have in principle endless top growth, have less storage capacity but may be protected by an evaporation-resisting cuticula. These latter plants may vary between long and slender to short and compact. In the extreme case of the genus *Taeniophyllum*, stem and leaves are almost entirely reduced with assimilation is taken over by the roots.

Epiphytes live in an extreme environment, when rainfall is absent for some time the plants start experiencing water stress. A number of species are tolerant for this stress, others are very exacting for drought conditions. The same counts for shade and exposure conditions.

Environmental factors determining occurrence of orchids

The environment has a great impact on the kind of vegetation that is able to develop in a certain area. Rainfall is locally a major factor determining the species composition, both the seasonal pattern as well as the amount of rain, annually and seasonally. Other important factors are seasonal patterns and the amount of sunshine. Altitude above sea level determines average temperature: the higher an area is situated in the mountains, the lower is the mean temperature. Plants have a specific temperature range in which they are able to flower, set fruit and germinate; outside that range they are unable to reproduce. Vegetation zones in the tropics are roughly distinguished in:

0-1000 m: Lowland forest
1000-3000 m: Montane forest
Above 3000 m: Subalpine forest to alpine vegetation

Each zone has its specific species composition. That is obvious for the trees which form the vegetation, but this is also true for orchids: many species are confined to one of these three zones. However, many other orchid species occur in a very wide altitudinal zone. Within these zones the environment can vary considerably, often caused by edaphic factors like drainage, texture of soil and relief. Orchids do not grow in submerged conditions but are found in almost all other environments.

Mangroves grow in an environment which is harsh for the trees and most cannot prevent salt entering their tissues. This evidently affects the epiphytic orchids with only a few species able to grow there. Due to daily inundation there are no ground orchids in mangroves. Fresh water swamps are periodically inundated and the water supply is nutrient rich. These forests lack terrestrial orchids, while epiphytes can be abundant.

Figure 73. ***Dendrobium alexandrae.*** **Rather common in cultivation, but only 3 specimens with known localities preserved in Herbaria.** *Photo source: E. de Vogel.*

Figure 75. ***Glomera*** **species.** *Photo source: E. de Vogel.*

Figure 74. ***Oberonia rivularis.*** **Large plant with numerous minute flowers.** *Photo source: E. de Vogel.*

Figure 76. ***Dendrobium macrophyllum.*** **Common large species, very common in cultivation.** *Photo source: E. de Vogel.*

Peat forests grow on accumulating peat deposits. The margins of such forests on a peat dome support reasonably high trees with a rich orchid community. Towards the centre of the dome the trees become dwarfed and wider apart until they disappear almost entirely. Here orchids are almost absent.

Savannas are a harsh environment where precipitation can be virtually absent in a certain period of the year. Only very hardy, drought and fire resistant orchids can grow in this environment, where terrestrial orchids are found among the grass vegetation and epiphytes on the scattered trees.

Lowland rainforests have ample and regular supply of rainwater. They are usually composed of tall trees with a high canopy which receives direct sunlight. On the ground between the trunks there is very deep shade and usually little undergrowth. Very even temperature and moisture conditions are present on and near the forest floor, and there is a very low light intensity, with an occasional light spot. This variation in conditions produces many different niches where orchids can thrive. Terrestrial orchids and epiphytes can be abundant. Terrestrial orchids are mostly found along streamlets and in the wetter areas. Bole epiphytes are not very common. Canopy epiphytes can be abundant but are difficult to spot because they grow 25-40 m above the ground. Along bigger streams where leafy branches reach down they descend to the water level and are more obvious.

Heath forest is a light, rather open kind of forest on white sand, usually with a podsol soil profile underground which causes pools of stagnant water. The light conditions under the canopy allow trees to maintain lower branches. Orchids enjoy these conditions, and are abundant on branches and trunks, as well on the forest floor. The same occurs in forests on ultrabasic soil.

Hill forests from 500 to around 1,000 m above sea level grow on sloping to steep terrain with good drainage and streamlets which offer all kinds of environments suitable for orchids. Crowns of trees on the slopes receive on one side more light than on the other side. Orchids can occur here in moderate to staggering abundance. Terrestrial orchids are found on slopes and especially along streamlets.

Lower to upper montane forest up to 3,000 m form a dense tree cover over undulating to steep terrain provided with streamlets. The temperature is cooler than in the lowland areas. Conditions are in general continuously wet, with daily accumulation of clouds and in the afternoon, downpours. Here epiphytic orchids are found in great abundance and diversity, especially between 1,500 and 2,500 m where the greatest orchid diversity is present. Terrestrial orchids are common and most abundant along streamlets.

Patchy areas of subalpine forest and subalpine grassland above 3,000 m support a less abundant orchid flora. Trees can still be covered in orchids but the species diversity is much lower. The grasslands support a limited number of terrestrial orchid species.

Alpine vegetation above the treeline supports a relatively poor orchid flora consisting partly of species which also grow lower down on the mountain as epiphytes.

Figure 77. ***Rhinerrhizopsis moorei.*** **A common species all over New Britain.** *Photo source: E. de Vogel.*

Figure 78. ***Diplocaulobium auricolor.*** **Earlier known from mainland New Guinea and then discovered to be rather common in New Britain by the Flora Malesiana: Orchids of New Guinea project.** *Photo source: E. de Vogel.*

Figure 79. ***Bulbophyllum ascochilum.*** **A species described in the Flora Malesiana: Orchids of New Guinea project.** *Photo source: E. de Vogel.*

Figure 80. ***Dryadorchis dasystele.*** **A species described in the Flora Malesiana: Orchids of New Guinea project.** *Photo source: E. de Vogel.*

Impact of forest disturbance on orchids.

Major threats to Papua New Guinea orchids come from two main sources, the destruction of habitat and over-collecting of certain species. The large variation in tolerance of different orchid species to environmental changes, as explained above, makes it difficult to give a generalised outline of the effect of forest disturbance on changes in orchid species composition.

Destruction of habitat

The removal of a single tree will have no impact on the orchid population in a forest, except for the plants on the fallen tree. These plants will die due to moister conditions and shading on the forest floor. The opening in the canopy is small and the succession is comparable to the natural succession of trees in a mature forest. Making larger gaps will change the water balance in the opened area. Orchids will not survive in areas where the trees are gone; the epiphytes miss support hosts, terrestrials miss shade and moisture, and mycorrhiza are killed by the change in conditions. Orchids in the adjacent undisturbed forest may suffer from drought stress and either die or barely survive till the canopy is closed again by saplings, pole trees and climbers filling the gap.

Industrial logging, which commonly covers an extensive area, has a different effect on the forest. In the initial phase of logging an undisturbed area of forest is opened up. First the main logging roads are made to create a road grid to access the area. Usually these roads are flanked by ditches for the drainage of rain water. The stretches cleared are much wider than the actual roads, to dig draining ditches and to allow sunshine in to facilitate quick evaporation of rainwater after showers to dry the road surface. This is the initial start of a gradual process in the forest in which the water balance is upturned. Subsequently, smaller logging roads are made, often in a fine grid, to extract the wanted

Figure 81. *Bulbophyllum fritillariiflorum*. A species formerly known from 2 localities in Papua, Indonesia, and PNG, discovered to be not uncommon in New Britain by the Flora Malesiana: Orchids of New Guinea project.
Photo source: E. de Vogel.

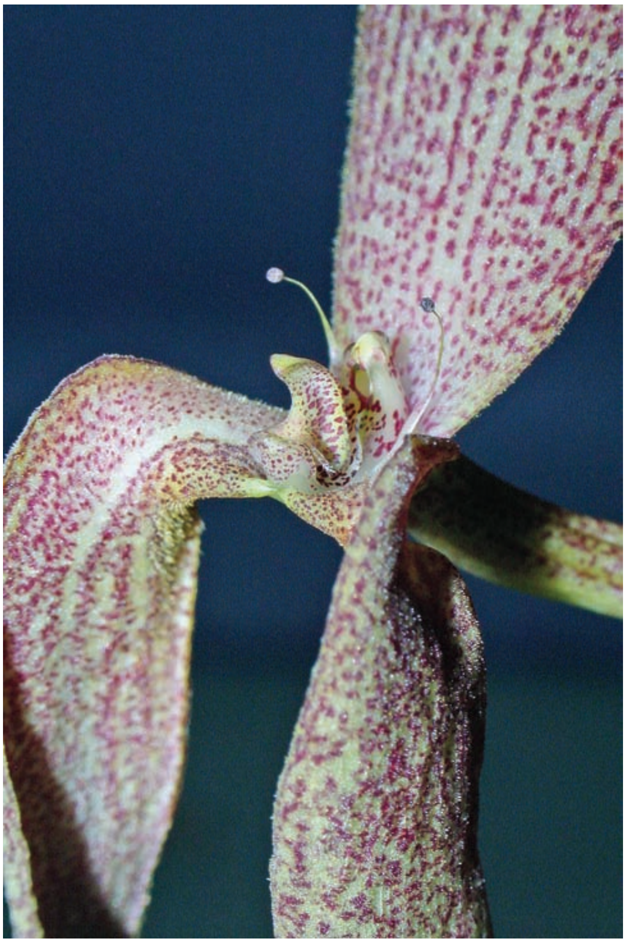


Figure 82. *Bulbophyllum bandischii*. A rather common species in New Britian and New Ireland. *Photo source: E. de Vogel.*

trees. During this process often small valleys are blocked where pools of stagnant water are formed. The canopy is opened to a various extent, whereby falling trees damage crowns of undergrowth shrubs and other trees which are not planned to be harvested. Sometimes several trees that are not wanted come down with the cut tree when they are tied to it by lianas. Over large stretches random numbers of trees are removed, sometimes in patches, sometimes solitary trees only. The crowns are removed from the log and left in the forest. Small bulldozers enter the vegetation to pull out logs, in this way destroying and damaging undergrowth vegetation, saplings and pole trees further, and compacting the soil and creating more pools. Stumps, branches and litter decompose in the soil or in puddles of stagnant water. This opening up of the forest will totally disrupt the water balance in the remaining vegetation. All orchids brought down by the logging will die, and terrestrials are crushed by the bulldozers. Many orchids on the remaining standing vegetation will linger on for some time but depending on exposure and environment preferences many orchid species will disappear sooner or later from the area. Pollinators of orchids will find their habitat conditions in many cases so changed that they are unable to survive; rejuvenation of the orchid population is thus seriously reduced or absent.

Not all tree species support the same amount of orchids. This depends on bark type, chemicals in the bark, etc. Of those species that support orchid populations, adult trees support more orchid specimens and species than younger specimens due to more accumulation of humus and/or decreased defense against mycorrhizal fungi due to senescence of their living cells.

After logging this damaged vegetation is left for two to three decades to recover. In general an initial growth occurs of herbaceous climbers which cover the open areas and remaining trees, thus bringing in shade, and partly restoring the water balance. Saplings and pole trees in the less damaged areas are able to recover and grow up slowly to adult size, thus suppressing and squeezing out the climbers. This way the canopy will be closed again, water balance is slowly restored, and some orchid species are able to move in again – that is, if there are seed sources of orchids in the neighbourhood. It remains to be seen if many of the pollinators will return, as hardly anything is known about them. The longer the forest can grow, the better the recovery of the orchid flora will be.

After 25 to 30 years the trunks of the former saplings and pole trees will have grown to harvesting size. Since they were not adult during most of this period no rejuvination of the trees has taken place, so no or hardly any young stock of these trees is present. Often now a second logging activity takes place. This damages the vegetation to such an extent that both the forest and the returned orchid species will be barely able to recover. The tree vegetation dries out very seriously, and is liable to burning in dryer periods. In many cases such remains of forest are totally cleared, and nowadays they are often turned into oil palm plantations. These are orchid deserts where hardly any orchid will grow.

Shifting cultivation has another effect on the forest, and hence on the orchids. A patch of forest is entirely cut down, the trees are left in situ to dry and are then burned to provide minerals for the crop which is planted. The burning will kill all orchids in the patch and in the closely surrounding forest. Crops will be planted, and after harvesting the land is abandoned, and weeds take over, covering the soil. A succession takes place from a herb vegetation through a shrub vegetation to a secondary forest. The vegetation becomes higher by the years, and gets a more and more stable water balance. Young secondary forest turns in a few decades in steps into old secondary forest with a different species composition and a better water balance. Very few orchids feel at home in young secondary forest, only some terrestrial and some epiphyte species. The older the secondary forest becomes, the more orchid species it will harbour. If patches of primary forest remained in the neighbourhood there is a seed source from which seeds can invade to supply primary forest tree species and the secondary forest will slowly turn into a primary forest again. This process takes more than a century. Orchids, if they survived in the remaining primary forest, will return gradually back in this recovering forest. When conditions are favourable, the return to primary forest will take at least a century.

Nowadays the scale of shifting cultivation has enlarged to such an extent that there are areas where hardly any patches of primary forest are left. Shifting cultivation will here turn primary forest into permanent secondary forest with a very sparse orchid population. In areas with a more pronounced dry season, activities by the local population will lead to the development of a grassland vegetation - a fire climax. Only very few terrestrial orchids are able to survive in such ecosystems, generally only those with deeply burrowed tubers and fire resistance.

In several areas in PNG, forests occur which have a normal structure and physiognomy, complete with undergrowth, tree juvenation and large ground orchids, in which one thing is abnormal: small terrestrial orchids and epiphytic orchids are entirely absent, or only very few of these orchid plants are found. Such orchid deserts have been encountered in a coastal forest on Ferguson Island, in a lowland forest in the Gulf Province, and in a hill forest in the Waria valley near Garaina. This unnatural phenomenon was in all three cases attributed by the local population to the severe drought period in 1997 during El Niño. Many forests burned in that year, but some survived, although they dried out very severely, by which exposed epiphytic orchids and small terrestrial orchids were almost entirely eliminated.

Forest conservation and orchid conservation

From the last chapter it is clear that the more extensive the disturbance is, the more the orchid flora is affected and the longer the restoration will take. The measure of recovery depends, amongst other factors, on the availability of seed sources of orchid species in the neighbourhood, survival of pollinators, presence of support trees, recovery of the water balance, etc. Some of these factors are beyond human control, but others may be influenced by decisions made at government level in the license granting phase for logging companies, or in the production phase of logging. Logging concessions do not need to share boundaries. Corridors of undisturbed forest can be left between them, allowing for orchids to disseminate from those areas. Conditions can be put in logging company licenses that they should spare several pockets of undisturbed forest in their concession in which they do not extract trees. Or companies themselves could decide to do that, and use it in the publicity on their activities, by which they certainly would acquire positive reactions from nature conservation agencies and the general public.

Collecting and over-collecting of orchids

The second major threat to Papua New Guinea orchids comes from over-collecting of certain species for cultivation. Distinction must be made between collecting by amateur orchid growers for private use, commercial collecting for trade, and collecting for scientific purposes.

Collecting by amateur orchid growers aims in general at obtaining one or a few specimens of desired species from a population, and usually concerns a limited number of species. The aim is not to acquire financial gain but to obtain specimens for one's hobby. When the orchids are locally grown in gardens and remain in the area they will produce seeds which will be dispersed in the surroundings and help keep the populations of the species stable. An example are species of *Dendrobium* section *Diplocaulobium* which are grown in masses for decoration on the coping of the roofs of local houses. These plants have mass flowering some days after a cold rain shower. It is a spectacular sight when all plants turn the coping into a white rim. However, when the orchids are removed from the local area, then they do not contribute to keeping up the wild orchid population. Collecting for private use is in general not detrimental to orchid populations when collection pressure is not extreme.

Commercial orchid collecting is searching for species with spectacular flowers and/or inflorescences that are long-lasting. Such practices can lead to over-collecting by removing the large majority if not all specimens of a desired species from a population. The aim is to acquire specimens for financial gain. These plants are always removed from the area where they were collected, and this can seriously hamper rejuvenation, and even lead to complete depletion of populations. On the website OrchidsPNG.com extensive exploitation of orchids was reported in the period 1990 till 2000, despite enforcement of a ban on export of wild collected orchids from the country. At present, commercial collecting for illegal export of orchids does not seem to be a major problem any more. In Europe and America hardly any orchids are offered for sale that originate from Papua New Guinea.

Collecting for scientific purposes is comparable to collecting by amateur collectors because the aim is to collect only few specimens per species from a certain area. The purpose is to acquire knowledge about the orchids. The most important reason for scientific collection in PNG is to develop an inventory of the orchid flora of the country. For inventory collecting, where a specialist collects, it can involve only collecting orchid plants of one or a few genera at a time. This type of collecting can lead to large orchid collections, despite the fact that care is taken to collect only one or two specimens per species. Inventories of PNG orchids have in general been undertaken jointly between PNG institutes and orchid specialists from a country abroad. This is because in PNG no orchid specialist is available with an overall knowledge of orchids, hence cooperation with specialists abroad is the only way for the country to acquire knowledge about their own orchid diversity. An orchid can in general only be correctly identified when it is flower. However, orchids in the field are most of the time sterile, usually fewer than 10% are in flower. Consequently the remaining 90% or more of orchids collected in the field cannot be identified. Such a specialist is then allowed to take one set of the orchids to his country to grow the plants into flowering and provide names when that occurs.

In PNG orchids are classified as minor forest products and they are considered a renewable resource that can be utilized. A few attempts have been made in PNG to exploit orchids as a renewable resource and establish a viable orchid industry, but all efforts thus far have not been adequately funded to get these enterprises off the ground. A major tourist attraction, the Lady Veronica Somare Orchid Garden, was established recently in the vicinity of Port Moresby. It exhibits only spectacular species and hybrids of a limited number of orchid species from a very limited number of orchid groups.

The Port Moresby Nature Park, the former National Capital Botanical Gardens, used to be specialised in making new hybrids of spectacular orchids by crossing native orchid species. It maintains a small collection of live native orchids which also includes many less spectacular species. Since the name change, its activities have focussed more on exhibiting animals, but plans exist to pay more attention to the variety of native orchids. It has potential to grow into an institute that demonstrates the richness of the unique PNG orchid flora. Ideally there should be a lowland and a highland facility to demonstrate the complete range of this flora, since the highland orchids are more diverse than the lowland ones. But expansion of the lowland facility with a much completer and better maintained collection would be a good start.

In Papua New Guinea, orchid research has been limited to taxonomic research done by visiting scientists, some long-term expat residents and by a few private growers. Unfortunately in the country not a single professional botanist is specialised in orchids. This means that any progress in knowledge of PNG orchids is dependent on scientific work done by specialists in institutions abroad. Since 2003 the Flora Malesiana Orchid Project of the National Herbarium Netherlands, now Naturalis / Hortus botanicus Leiden has been cooperating with the Department of Environment and Conservation (DEC), the National Research Institute (NRI), the National Capital Botanic Gardens Port Moresby and later with the PNG Forest Research Institute. Live orchid plants were collected for these institutes in PNG and The Netherlands. The Hortus / Herbarium in Leiden received CITES permits for export of orchids in order to cultivate them into flowering to obtain identifications. CITES refers to the "Convention on International Trade in Endangered Species of Wild Fauna and Flora". This work has resulted in a few thousand identifications to genus, section or species. That information was used to expand and improve existing information, and this was published on the 6 CD ROMs mentioned before. These CDs were donated to all Institutions and some private persons in PNG for which the information was relevant. This information is now in the process of being transferred to a website by Naturalis Biodiversity Center in The Netherlands, which will be made freely available to the public.

In Papua New Guinea protection of wildlife is controlled by Department of Environment and Conservation (DEC). The CITES office is the branch of this Department that controls the export out of PNG of wildlife protected under the Washington Convention of Threatened Plants and Animals. This includes all orchid species. CITES export permits are required when orchid plants leave the country. This applies to orchids collected by amateur collectors, for private use, for commercial purposes, and also for scientific study.

It would be expected that National Research Institute and Forest Research Institute possess a key position in directing the inventory and study of orchids, since they are in charge of developing scientific policies for the country. With the lack of orchid experts in the country, cooperation with institutes abroad is the only way to increase the knowledge of PNG orchids. For that purpose it is necessary that experts in those institutes are allowed to study PNG orchids. Since there are no large scale facilities in PNG to grow orchids into flowering and no funds to send spirit and herbarium specimens for study to other counrries, institutions abroad are willing to cooperate and offer growing facilities for live plants in their country, and supply expertise to help understand the orchid flora of PNG. That is a well-tested method as mentioned earlier; generally a very low percentage of the orchids encountered in the field are in flower, that means that more than 90% of the species in an inventory cannot be identified. Growing these plants into flowering can raise this identification rate to over 60%.

While it is clear that advancing the scientific understanding of PNG's orchids requires some export of specimens to overseas institutions for identification, there are institutional barriers preventing this from running smoothly. One barrier is opaque decisions regarding the granting of export permits. DEC/CITES has control over the export of orchids to and from PNG. Naturalis Biodiversity Center cooperates already since 2003 with National Capital Botanic Gardens Port Moresby for which NRI provided the principal investigator of the Orchid Project with a Special Exemption Researcher / Academic Permit, which was renewed every three years. In 2008, DEC requested from Naturalis to arrange a co-operation agreement on the scientific study of PNG orchids with FRI, which materialised in 2010. However, in 2012 export permits were refused by DEC, without supplying reasons. Given that the role of DEC is to protect and conserve wildlife, and the goal of the international co-operation in question is to understand, protect and conserve PNG's orchids, the reasons for refusal are unclear. The consequence is a stalling in the inventory, study and understanding of PNG's orchids. This could be overcome by DEC through developing and applying clear and consistent guidelines for the granting of export permits.

A second institutional barrier to the scientific understanding of PNG's orchids is again opaque decisions by DEC/ CITES PNG. In Naturalis in the Netherlands, herbarium specimens and spirit samples collected from cultivated collections of PNG plants are accumulating to be returned to PNG. Both amount to many hundreds. The Dutch CITES office is intended to be self-supporting, it requires forms to be bought to both import as well as re-export these specimens to PNG. An Export Permit costs 60 Euro, and can contain only one species name. Appendixes (each also 60 Euro) can be attached, each form can contain maximum 3 species names. For sending back specimens of 500 species, this administration requires Naturalis to pay 10,000 Euro! CITES headquarters in Swizserland has made a provision which circumvents paying fees for export / import of recognised scientific institutions, the CITES Registration Number. An institute with such a number is not required to pay fees for receiving specimens or sending them abroad. Naturalis Herbarium is registered as NL 008 under this system, and can exchange specimens with other registered institutes without paying such fees. However, CITES PNG has blocked this possibility for PNG FRI, despite that several letters have been written by that institute requesting to obtain a CITES registration number. Naturalis wants to meet its obligations to PNG FRI to send these collections back, but cannot afford paying several tens of thousands of Euros for fees while with a registration number for PNG FRI no fees are required at all. This could be overcome by CITES PNG granting PNG FRI a CITES registration number, by which those specimens could be returned to PNG for free, without paying exorbitant CITES administratiuon costs.

Conclusion

New Guinea is one of the richest parts of the World in orchid diversity. At the same time, our knowledge of its orchid flora is still very much incomplete. Large-scale deforestation is becoming a severe threat to orchid diversity in PNG . Unless conservation measures are taken and scientific inventory work is greatly expanded, there is a great risk that numerous orchid species will be lost before they are even discovered and named, let alone conserved. Clear and consistent policy for cooperation on the study of orchids with scientists abroad including CITES export permits for orchids will greatly improve inventory and understanding of PNG's orchids.

Chapter 7

The flora of New Guinea: its origins, affinities and patterns of diversity and endemism

Osia G. Gideon

Osia Gideon is Associate Professor and Head of Biological Sciences Division at the University of Papua New Guinea. He was previously Deputy Director of PNG Forest Research Institute, and recently has been appointed Professor in the Department of Forestry, PNG University of Technology. He has a Diploma in Forestry (Bulolo), Bsc (For.) and M.Phil. (PNG Unitech), and PhD (James Cook University). He is a Fellow of the Linnaean Society and member of several professional scientific societies. He has spent all of his 36 years of professional life in research and academia in PNG.

His research interests include plant systematics; plant diversity and conservation; New Guinea biogeography; the history of New Guinea botany; and sustainable use of biodiversity.

Introduction

New Guinea is the largest and highest tropical island in the world. It is one of the last biological frontiers and has long fascinated biogeographers by its very peculiar endemic biota, showing both Asian (many groups of plants and insects) and Australian (mammals, reptiles, etc.) affinities. The island is extremely rugged, having the highest mountains in the Southeast Asia-Pacific region. A rugged mountain range (the Cordillera) is located in the centre of the island, with a number of peaks reaching at least 4,000 m altitude (e.g. Mt. Jaya 4,881 m, Mt. Trikora 4,750 m, Mt. Mandala 4,702 m, Mt. Wilhelm 4,510, Mt. Giluwe 4,368 m). It is one of only three tropical regions with glaciers. The island has a moderate to very high rainfall, spread through most of the year, with temperatures ranging from 30–34°C (15–30°C in the highlands), with high relative humidity.

New Guinea is truly unique, as succinctly described by Gressittt (1982). The island has a young complex geology dominated by a central (cordillera) spanning almost the entire island and surrounded by flatter coastal lowlands. Due to the tropical latitude, in combination with rugged topography and high elevations, a wide range of ecosystems are found in New Guinea, from cold alpine grasslands, to wet lowland rainforest, and seasonally dry savannahs. New Guinea flora and fauna have affinities with both Australia and Southeast Asia, and as a result of the geological complexity and varied climate, the flora and fauna are highly diverse, and highly endemic. Papua New Guinea is recognized as one of 17 megadiverse countries in the World (Mittermeier *et al.* 1997). This diverse and peculiar biota reflects the geological history and the physiographic diversity of the island.

Figure 83. *Saurauia* sp. nov. (Actinidiaceae), an undescribed species from Woitape Area, Central Province. A large genus with many endemic species.

The history, ecology and distribution of New Guinea flora is still poorly understood. Despite this lack of knowledge, or perhaps because of it, New Guinea is one of the most exciting regions of the World in which to study plant biogeography. The island is a meeting point for the Malesian and Austral-Pacific floras. It is thought that there are somewhere between 11,000 and 25,000 species of vascular plants in New Guinea, perhaps as high as 30,000, and a conservative estimate indicates about 50% of species are endemic to the island (van Welzen 1997, van Welzen *et al.* 2005). For angiosperms, species endemism may be as high as 90% (Good 1960). Our knowledge of the origin and affinities of the New Guinean flora is based mainly on reviews at the genus level, as well as biogeographical analyses (e.g., Good 1960; van Balgooy 1976; van Steenis 1979; Hartley 1986). Few studies of patterns of plant species diversity have been published on a global scale, and most do not use a consistent methodology which means few solid conclusions can be drawn (Barthlott *et al.* 1996, 2005; Mutke & Barthlott 2005; Kier *et al.* 2005). However, these studies indicate that New Guinea is one of five centres that reach species richness of more than 5,000 species per 10,000 km^2 (the others are Costa Rica-Chocó, Atlantic Brazil, Tropical Eastern Andes, Northern Borneo). A key feature of these five centres is that they are both mountainous and tropical.

With long isolation from other landforms and many unique habitats, speciation events have contributed to the high diversity and endemism of New Guinea's flora. The same characteristics that make New Guinea a special place also mean that without adequate conservation planning, habitat loss mainly due to human activities may cause major species losses in the future.

Geological History

A discussion on the origins of a flora must begin with a discussion of its geological development. New Guinea lies in a zone of active plate tectonics. About 130 million years ago (MA), components of New Guinea were part of the pre-historic continent called Gondwanaland, and during the Cretaceous parts of it began to break apart and larger pieces like Africa, India and South America drifted away. Southern New Guinea was part of the Australian continent, which began breaking away from Gondwanaland about 125 MA.

The Miocene and Pliocene (23 - 2.6MA) was a period of active volcanism in the region. The major tectonic plates around proto-New Guinea (the Australia/New Guinea Plate and the smaller regional subplates: Solomon, Bismarck & Caroline Plates), converged in a series of complex events, and there were major land deformations and uplifting as a result (Davies 2012). The ongoing northward movement of the Australia/New Guinea plate led to continued convergence with adjacent tectonic plates (Davies 2012). The southern half of present day New Guinea and the Arafura Sea overlies the Australian Craton, relatively stable compared to northern New Guinea.

Successive periods of plate convergence, uplift, folding, faulting and volcanism over time caused different portions of continental and oceanic crust to be accreted together (terranes) at different times. This understanding that New Guinea was made up of terranes marked a major milestone in understanding its geological history (Pigram & Davies 1987, Davies 2012). The terranes are fragments of oceanic crust and mantle, as well as blocks of volcanic arc, and there are two great ophiolites (uplifted segments of rock present on land that were once ocean crust and mantle). The terranes that make up present day northern New Guinea had been accreted by the end of the Miocene (10 MA), the last and most complex terrane system (the Vogelkop Peninsula) was accreted in the Pliocene (5 MA) (Polhemus & Polhemus 1998, Davies 2012). This new knowledge has greatly influenced our present views of the geology and biogeography of the region.

Present day New Guinea continues to experience uplift. In the Huon Peninsula, average rates of uplift of 1-3 mm annually have been recorded, which is substantial when viewed over geological time (Davies 2012). While the region has continued to be tectonically active, the position of the terranes is much the same as up to 2 million years ago. The islands in the Bismarck Archipelago and the Solomon Islands are thought to have formed through periods of volcanism separate from the geological development of the main island of New Guinea (Davies 2012).

Figure 84. The famous Huon coral terraces, formed as the Huon Peninsula emerged in response to arc-continent collision, rising to 600m and preserving a record of sea level fluctuation for the last 300,000 years. (From Davies 2012, reproduced with permission).

Vegetation History

New Guinea's geologic and climatic past, especially changes during the Quaternary period (2.6 MA to the present day), have had a profound influence on present day vegetation in New Guinea. Ancient fossilised remains, especially plant pollen and spores, have been used to reconstruct the history of vegetation in New Guinea. Pollen in particular has provided evidence of major changes in PNG's flora over time, and these changes have reflected major climatic changes. For example, pollen records indicate the tree line (limit of tree growth) in New Guinea (currently at approximately 3,900 m elevation) may have been as low as 2,200 m during glacial periods (Walker & Flenley 1979).

Figure 85. The remaining icecap on New Guinea mountains, as seen here from Mt. Jaya in West Papua at 4,884 m altitude. Photograph by H.L. Davies in 1995 (Davies, 2012), reproduced with permission.

The climate of the Quaternary period in New Guinea has been marked by periods of much cooler, dryer and more seasonal conditions during which it is thought seasonally dry ecosystems and lowland grassland developed (eg. around Port Moresby) (Walker & Hope 1982). Rapid climate change occurred with successive periods of cooler climate when large glaciers formed and sea levels dropped (glacial periods), and warmer periods when glaciers melted and sea levels rose (interglacial periods). Sea levels during the Quaternary have fluctuated up and down by up to 140 m (Hope 1996, 2007). For most of the past 100,000 years, sea levels have been 20 - 60 m lower than present, but 22,000 years ago sea levels were about 110 m lower (Hope 2007).

The fluctuation between glacial and interglacial periods during the Quaternary (and perhaps even earlier) created a very unstable environment for plant development in PNG (Walker & Hope, 1982). Added to the climatic variability was the geological instability, as major periods of volcanism, uplift and land deformation were also ongoing. Perhaps one of the most direct effects of lower sea levels during glacial periods was the connection of lands previously divided by ocean, such as the drying of the Torres Strait. Consequently, for much of the Quaternary, Australia and New Guinea were connected by dry land, and two previously separated sets of flora and fauna began to interact. The lower sea levels and cooler mountains of the glacial periods offered new niches, allowing migration and establishment of a tropical alpine flora. The present New Guinea coastline has developed since the last sea level rise, and we are approaching the end of an interglacial period called the Holocene (Hope 2007).

Details of Quaternary climate change remains little known and based on much speculation, but the climatic fluctuations have no doubt influenced the frequency of extreme events like droughts and unusual frosts, cyclonic storms, and also the frequency of fire. Fossil records of pollen, charcoal and other particles have been used to describe changes to vegetation in response to climate and the arrival of humans (Hope 2007, Hope 2009). Early human occupation of the New Guinea highlands is evidenced by the presence of charcoal, denoting fires, and human derived landscapes such as woodlands, grasslands and savannah (Hope and Haberle 2005). The pollen records also indicate that closed lower montane forests have occupied many areas despite early human occupation. Hope and Haberle (2005) suggested that most of the lowland plains in the Sepik, Upper Ramu, Markham and Popondetta may have been drier during the Pleistocene than at present, with woodlands dominated by Nauclea and subject to frequent fires.

The timing of the arrival of people to New Guinea remains controversial, but there is enough evidence to suggest that humans have occupied New Guinea for more than 32,000 years (Hope & Haberle, 2005). The oldest evidence of human presence in New Guinea was stone tools from a raised marine terrace in the Huon Peninsula, which was dated to about 48,000 years before present (BP) (Groube *et al.* 1986). New Guinea vegetation underwent substantial changes after humans arrived (Haberle 2003). Evidence of human use of burning and clearing of forests for agriculture is present in the fossil records from the PNG highlands as far back as 7,000 BP (Denham *et al.* 2003, Haberle 2003, Haberle 2007). The fossil record showed clearing and burning for agriculture intensified over the last 7000 years, and this trend continues to this day (Shearman *et al.* 2008, Chapter 1).

The New Guinea rainforests have been shown to be rather dynamic and unstable ecosystems (Johns 1986, 1990). Aside from the historical instability and human impacts on the vegetation, natural disasters such as volcanic eruptions, cyclones, floods, landslides, lightning and drought related fires continue to affect New Guinea's vegetation and flora. Although, these natural caused disturbances may be small, their combined effect on the vegetation can be quite significant.

Origins, affinities, and endemism of the New Guinea flora

Origins of the Flora

The origins and affinities of the New Guinea flora have been longstanding challenges attracting the attention of biogeographers. This is mainly because of its strategic location between the biotas of Asia, Australia and the Pacific, and also the contrasting differences between its flora and that of Australia. The origins and relationships of the New Guinea flora cannot be determined with absolute certainty until it has been fully treated at species level. Because of the paucity of data many suggestions or hypotheses about the origins, diversification and affinities of the flora must remain tentative. Recent advances in our knowledge of New Guinea's geological and climatic history, and phylogenetic studies for a growing number of important plant families have provided some insights into the origins and evolution of New Guinea's flora.

Even though the flora of New Guinea is still very poorly known, some attempts have been made to discern the origins and affinities of this rich flora (Lam1934; Good 1960; van Balgooy 1976; Hartley1986; van Welzen 1997; Heads 2001). Most of these analyses were genus based, and some consensus has been reached about New Guinea's flora: (1) that present flora is dominated by two main elements, the ancient (autochthonous) Gondwanic element which arrived via the Australian continent and an immigrant Asian element which arrived from the west and north, when the Australia/New Guinea plate came into contact with the Sunda Shelf; (2) that the flora is strongly dominated by the immigrant Asian element, which is estimated to represent between 30% and 60% of the flora at genus level (Van Balgooy 1976; Hartley 1986); (3) that species endemism is extremely high, probably as high 70-80%.

The oldest element in the flora is the autochthonous Gondwanic element, which mostly exists now in moist, cool climates, like those found in upland New Caledonia, New Zealand, Tasmania and Tierra del Fuego. Fossil pollen of related taxa have also been found in Antarctica (Hartley 1986). This Gondwanic element includes taxa such as the families Cunoniaceae, Araucariaceae, Podocarpacae and Winteraceae, and the genera *Helicia*, *Nothofagus* and *Pittosporum*. In New Guinea this element is found mainly in the mountain forests (Hartley 1986), where these species are dominant and are usually endemic. This ancient Gondwanic vegetation may have been present in New Guinea, throughout the region's history since Cretaceous times, as suggested by Smith (1974, 1975). An alternative explanation is that this element migrated from then mountainous Queensland during the late Tertiary into the newly forming mountains in New Guinea (Schuster 1976; Walker 1972). Whatever the explanation, colonisation of New Guinean mountains would have occurred overland, and gradually. When the Australia/New Guinea continent and the various terranes coalesced to form the present New Guinea landmass, a vigorously changing landscape was created. This dynamically changing environment provided ideal conditions for the autochthonous element to diversify and occupy the newly created niches on the mountain tops. When the Australia/New Guinea continent came into contact with Asia during the Miocene, the autochthonous Gondwanic flora was joined by the immigrant 'Asian' or 'Malesian' element, which was later to dominate the New Guinea flora.

The dominance of plant taxa of Asian origin in the flora of New Guinea has attracted much attention for several decades, perhaps more for the fact that Australian taxa are poorly represented in the flora, even though New Guinea is only 120 km from the tip off the Cape York Peninsula (Good, 1960; van Balgooy 1976; Hartley 1986). This Asiatic element was previously thought to be of Laurasian origin, but there is now strong evidence to suggest that this may be mostly of Gondwanan derivation. India and various fragments that rifted off from the north east edge of the Australia/New Guinea plate may have played a role in bringing the Gondwanan element to Southeast Asia, which eventually reached New Guinea (Morley 1998, 2001). Some of the taxa that dispersed from the Indian continent to Southeast Asia included *Durio*, *Gonystylus*, *Ctenolophon*, Sapindaceae and Iguanurinae. The Sapindaceae reached West Malesia mostly via the Australia/New Guinea continent, but there is evidence of dispersal from India as shown by the *Litchi* pollen type (van Welzen & Turner 2001). Even though India's role as a source of Gondwanan flora in Southeast Asia is considered insignificant by some, tectonic reconstructions of its size and positions during its journey to Asia indicate that exchange of flora with West Malesia was very likely, even prior to its collision with Southeast Asian in the Late Oligocene (approximately 26 MA) (Morley 1998). Before its collision with Southeast Asia it had come close enough to parts of Malesia, such as parts of Borneo, for early exchanges of floras to occur.

The geological history of the islands of Wallacea (Java, Lesser Sunda Islands, Sulawesi, Philippines and the Moluccas), especially Sulawesi and Philippines, hold the key to understanding the dispersal of this floristic element to New Guinea and beyond (Morley 1998, 2001). During Early to Middle Miocene, the Southwest arm of Sulawesi was part of the Sunda craton, firmly attached to Southeast Kalimantan. Formation of the Makassar Strait in Late Eocene due to rifting and crustal extension caused that flora of Asian affinity to become stranded to the east of Wallace's Line on emergent parts of southwest Sulawesi (Morley 1998, 2001). Mountains in Borneo, Sulawesi and the Banda Arc were formed via the collision of the Australian/New Guinea plate with Sunda and Philippine plates in the Early Miocene (Hall 2009). The the arrival of arcs from the Pacific in Wallacea area later led to emergence of islands in the region. This enabled the dispersal of flora with Asian affinities eastwards to Indonesia and New Guinea as these islands emerged as land masses above sea level (Morley, 1998, 2001). A second dispersal route of this Asian flora to New Guinea may have been via the Philippines and Halmahera (Morley, 1998, 2001). Dispersal of plants from Asia to New Guinea via these two routes is probably best exemplified by *Aporosa* (Euphorbiaceae), in which the Section Papuanae originated from West Malesian relatives and dispersed to New Guinea via the Tertiary island arc complexes (Schot 1998, 2004). *Aporosa* may have reached New Guinea via both dispersal routes. The formation of the island archipelago in east Indonesia also allowed dispersal of certain Australasian taxa to Sunda (e.g. *Phyllocladus, Podocarpus imbricatus, Staenochlaena milnei, Camptostemon, Casuarina, Phormium,* and Myrtaceae).

It can be concluded that the core of the present flora of New Guinea formed as a result of the intermixing the Asian derived element with the Australian flora in the Miocene. When the Asian floristic element reached New Guinea it was well differentiated and well adapted to tropical conditions, radiated rapidly and overran the autochthonous element. The autochthonous element had little success in the lowlands but more successful in colonizing mountain forests, having just moved into the tropics from temperate conditions in the south.

New Guinea is geologically a very active region with a history of climatic and sea level changes during the Quaternary. All the past and present environmental conditions have no doubt encouraged vigorous local speciation which is indicated by the occurrence in many genera of a series of morphologically very similar, sympatric 'species complexes' (e.g. *Drimys piperita, Chisocheton lasiocarpus, Guioa rigidiuscula,* etc.). Many plant genera have also undergone marked species radiations and with very high degrees of endemism in New Guinea (e.g. *Bulbophyllum*, 600/1200 (New Guinea/Worldwide); *Dendrobium*, 400/900; *Ficus* 216/800; *Psychotria* 200-300/2000; *Syzygium* s.l. 200+/1200; *Rhododendron*, 150/850; etc.). Van Welzen (1997) found that the highest number of endemic species occur north of the Australian craton margin. This region, formed via the complex successive accretion of terranes, is very geologically active. In New Guinea, the most diverse genera are located in the most unstable (geologically and climatically) ecosystems, where newly developing niches have been filled by the evolving species.

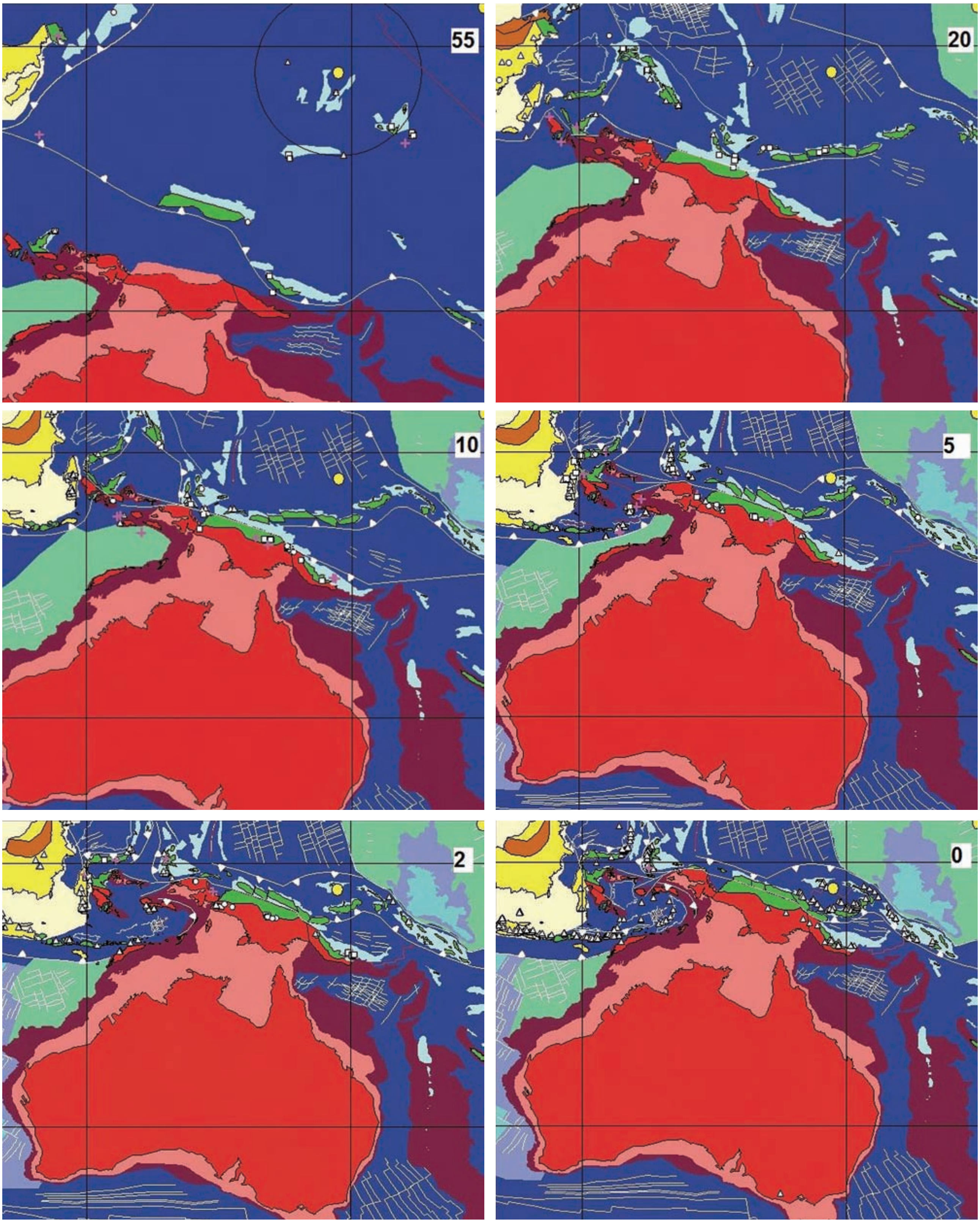


Figure 86. History of plate tectonics and terrane accretion of New Guinea over geological time. The location of the major tectonic plates and land masses at 55 million, 20 million, 10 million, 5 million, 2 million years before present, and the present day (0). Derived from Hall (2002).

Figure 87. ***Ficus itoana*** **Diels and** ***Ficus*** **sp. (Moraceae), two cauliflorous examples from one the most speciose genera in New Guinea (216 species, Berg & Corner 2005).**

Two further immigrant elements have been identified in the New Guinea flora: a "peregrine" element of both Asian and Australian origin; and a small monsoon savannah element of Australian origin. The peregrine element dominates the alpine and subalpine flora of New Guinea, and comprises mainly plants dominating mountain grasslands and other non-forest environments (Smith 1977, 1979). This peregrine element has much in common with other Malesian high mountain floras, such as those found on Mt Kinabalu and other high mountains on Java and Sumatra (van Steenis, Hamzah & Toha 1972; Smith 1977, 1979). It is now well accepted that the arrival of this element in New Guinea was quite recent, occurring only in the last few million years. During the Tertiary, major uplifting events produced rugged mountains in New Guinea, and during the Quaternary glacial periods sea-levels were lower, meaning that cold-adapted flora could migrate to the region and find suitable niches in which to establish (Holloway 1970; Raven & Axelrod 1972). Their affinities are various, some genera and species are clearly of Asian origin, such as *Rhododendron, Gentiana, Potentilla, Triplostegia glandulifera,* while others are obviously Australasian, like *Thelymitra, Uncinia, Coprosma, Styphelia suaveolens*. However, the largest category is plants of nearly cosmopolitan temperate affinity, such as *Carex, Poa, Plantago, Ranunculus, Montia fontana* and *Hypericum japonicum*.

In the Trans-Fly plains and around Port Moresby, the monsoon savannah element is predominant. Most of the larger trees in these woodlands are Myrtaceae of the genera *Eucalyptus, Melaleuca, Xanthostemon* and various species of *Acacia* and *Pandanus*. Shrubs, such as *Asteromyrtus, Banksia,* and *Hibiscus*, are common (Paijmans 1976). Most of the species are shared with Cape York and other tropical monsoon northern Australia, a clear indication that this represents an isolated fragment of a once continuous vegetation and flora across the Torres Strait (Bowman *et al*. 2010). The cratonic southern lowlands of New Guinea have remained a geologically stable region of the Australian/New Guinea plate, and have strong biogeographical affinities to the northern monsoonal tropics of Australia (Flannery 1995; Allen 2007; Allison 2007a, b; Beehler 2007a, b; Bowman *et al*. 2010). New Guinea was connected to Australia by dry land during most of the Quaternary, with a broad plain covering much of the present day Arafura Shelf and Torres Strait (Hope 2007).

Affinities and Endemism of the Flora

Because the New Guinea flora is of mixed origin, its affinities are also mixed, showing a complex of relationships. Few have attempted to analyse the present flora to determine its relationships, but this could only be done at genus and family levels because of the poor state of our knowledge at species level (Lam 1934; van Steenis 1954; Good 1960; Heyligers 1972; Hoogland 1972; van Balgooy 1976; Hartley 1986). The genus is used because there is at least general agreement on its delimitation than for species and families (van Balgooy 1976). Heads (2001) has rightly pointed out that the best data for any regional analyses of biodiversity are recently treated species taxa, and of course fully documented regional floras. Until the flora of New Guinea has been fully treated, we will continue to apply the genus as the main unit in any phytogeographical analysis of the flora. The few phytogeographical analyses of the flora have all cautioned that the data used were incomplete and any conclusions reached must be regarded as tentative, as they are simply the nearest approximations that it is practical to make under the present state of our knowledge (Lam 1934; Good 1960; van Balgooy 1987; Hartley 1986). Nevertheless, some general conclusions can be made on the characteristics and affinities of the New Guinea flora.

New Guinea has no endemic families, but shares a few small archaic families with Australasia (e.g. Corynocarpaceae, Eupomatiaceae, Himantandraceae, Trimeniaceae). Van Balgooy (1976) recognized 246 families in his analysis of the flora, and found that 41 Malesian families and 37 Australian families did not make it to New Guinea, while 20 Australian and Pacific families did not disperse further west beyond New Guinea, and 34 Asian families did not reach Australia, but some did reach the Pacific. New Guinea shares more families with Malesia than with Australia, and most of these families are well represented in both areas. Therefore, even at family level, the New Guinean flora shows stronger affinities with Malesia and the rest of Asia than with Australia. This is also true at the genus level (Table 7).

Another important element of the New Guinea flora is the high number of endemic or sub-endemic genera (Table 7), variously estimated as 9-13% over three different studies. A preliminary analysis of New Guinea alpine flora (Gideon, unpublished data) showed that 18% of the genera were endemic or sub-endemic, and 86% of the species are endemic. Some of the endemic/sub-endemic genera show vigorous speciation in New Guinea (e.g. Amaracarpus (31 spp), *Cadetia* (55 spp.), *Calyptrocalyx* (26 spp.), *Dolianthus* (13 spp.), *Sericolea* (15 spp.), *Tapeinochilos* (16 spp.). This endemic element is quite significant considering the instability of the landscape, thus suggesting that the evolutionary process has been going on for a considerable time.

New Guinea flora is more strongly related to Asia/Malesia than to Australia, and this relationship is strongly emphasised by the rainforest genera. However, if individual families were considered some would no doubt show strong southern affinities (e.g. Araucariaceae, Proteaceae, Cunnoniaceae, Myrtaceae, Sapindaceae, etc.). Because species endemism in the New Guinea flora is extremely high, it may not show such a strong relationship with the Asian/Malesian flora.

Table 7. Affinities and endemism of the genera as shown by three recent analyses of the New Guinea flora. .

Phytogeographer	Number of New Guinea genera			
	Total	Asian/Malesian affinity	Australian Affinity	Endemic/ Subendemic
Good (1960)	1,348	663 (49%)	188 (14%	140 (10%)
van Balgooy (1976)	1,465	686 (47%)	181 (12%)	195 (13%)
Hartley (1986)	716	413 (58%)	74 (10%)	64 (9%)

Patterns of diversity, distribution and endemism of the flora

Diversity and Distribution Patterns

Papua New Guinea, and Indonesia including West Papua, are two of the 17 identified megadiverse countries in the World (Mittermeier *et al.* 1997). As the flora of the New Guinea island remains poorly known, any attempts to identify patterns of diversity, distribution and endemism would be premature. However, it may be possible to detect some distribution patterns by extrapolating the limited data available. Plant distribution patterns are fundamental to the recognition, circumscription and understanding of areas of high biodiversity and endemism (Mittermeier *et al.* 1999). Barthott *et al.* (2005) have identified five global centres of high plant diversity, including New Guinea. Most of these centres are located in mountainous regions of the humid tropics, with suitable climatic conditions and high topographic and ecological diversity.

New Guinea is an important component of the larger floristic region called Malesia, which is among the most species-rich areas of the World (Roos 1993). The Malesian region stretches from the southern tip of Thailand, throughout Malaysia, Indonesia, the Philippines to Papua New Guinea. The region's floristic richness is estimated to comprise about 42,000 species (Roos 1993). The Flora Malesiana is a collection of volumes describing vascular plants of Malesia. However, since it started 60 years ago, only about 19% (8,000) of the estimated 42,000 species have been included. This makes any delineation of distribution patterns and areas of richness and endemism rather difficult. However, despite the limited data some authors have attempted to determine if any patterns can be detected for the whole region or parts of the region (van Steenis 1979; van Balgooy 1987; van Welzen 1997; Heads 2001; Roos *et al.* 2004; van Welzen *et al.* 2005).

Van Welzen (1997) analysed 961 endemic species from New Guinea to see if there was any relationship to the accretion history of the terranes, and he concluded that most distribution patterns can be correlated with the geological history of the island. Heads (2001) selected several recently revised specious New Guinea genera and mapped their occurrence in 1° grid cells. He found that the southern *Nothofagus* occurred predominantly on the Australian/New Guinea craton, whereas the Asian genera (*Parsonsia, Archidendron, Aglaia, Amyema*) have centres of diversity on the recently accreted terranes. These findings are not surprising as biologists have long recognized that ophiolites in northern New Guinea may represent important centres of species diversification and endemism (Vermeulen 1993; de Boer 1995; Turner 1995; de Boer & Duffels 1996; Polhemus 1996; van Welzen 1997; Heads 2001, 2002). However, it is only recently that it became clear that this interesting distribution pattern can be explained by the island's geological processes. Polhemus (1996) has provided an excellent review of the distribution patterns displayed by plants and animals on island arc systems, and regarded the ophiolites as important biogeographical arc terrane markers. Flannery (1995) has even pointed out that 'tectonic movements have been the prime cause of many of the zoogeographical patterns that we see in New Guinea today.' The northern New Guinea coastal ranges showed some of the most peculiar and inexplicable mammal distributions anywhere in New Guinea. The accretion of island arcs or terranes on the northern edge of the Australian/New Guinea continent over the last 40 million years is helping to explain plant and animal distribution patterns, each terrane may have its own particular distribution of flora and fauna (Polhemus & Polhemus 1998).

Recent analyses of plant diversity on a global scale have pointed out New Guinea as one of the world's centres of plant diversity (Barthlott *et al.* 1996; Mutke & Barthlott 2005; Kier *et al.* 2005). However, there is little consensus on the size of the flora (Womersley 1978; Frodin 2001; Collins *et al.* 1991; Johns 1993; Govaerts 2001). Estimates for the vascular flora of New Guinea range between 11,000 and 25,000 species, with some even as high as 30,000. Womersley (1978) conservatively estimated New Guinea's flora to be in excess of 20,000 species. Others have suggested different figures, e.g. Collins *et al.* (1991) gave 11,000, Höft (1992), 15,230; Roos *et al.* (2004) about 14,000; and Govaerts (2001), 16,200 species. Davis *et al.* (1995) estimated that New Guinea contains between 15,000 and 20,000 species, and with 70–80 % endemism, and that Mt. Wilhelm and surrounding areas possesses about 5,000-6,000 species. A rather generous estimate is the one given by Supriatna *et al.* (1999), who suggested that the Indonesian half of the island has about 20,000-25,000 species and about 90% endemism. Roos *et al.* (2004) argued that their estimate was based on verifiable extrapolations of data from Flora Malesiana, and that they considered their data to be representative of the region.

However, four of New Guinea's top six most specious families (Orchidaceae, Rubiaceae, Poaceae, Euphorbiaceae) have not been treated. When the Orchidaceae and Rubiaceae (first and second most specious families) have been fully studied, they are expected to reach over 3,000 and 800 species respectively, and they will certainly affect present figures on New Guinea's species richness and endemism. Other families that may also affect the statistics of the New Guinea flora include Annonaceae, Myrtaceae, Lauraceae, Gesneriaceae, Melastomataceae. Furthermore, there is no doubt some bias towards smaller families in the Flora Malesiana families treated so far. Good (1960) estimated that there are about 9,000-9,250 species of angiosperms in New Guinea, with 90% endemism.

Figure 88. *Tapeinochilos ananassae* (left) (Charlie Heatubun photograph) and *T. hollrungii* (right) from New Guinea. It is a genus of about 16 species and it is centred in New Guinea, with only three species occurring outside New Guinea.

Figure 89. *Psychotria* sp. (left) and *Timonius* sp. nov. (right), belonging to the Rubiaceae, the second largest family in New Guinea. *Psychotria* (c. 200 species) and *Timonius* (c. 80 species) are the largest and second largest Rubiaceae genera in New Guinea.

An evaluation of the phytogeography of New Guinea must be based on a list of all species occurring naturally on the island. Unfortunately, no such list exists and it will be many years before a definitive list becomes available, although the Flora Malesiana has the potential to provide these data. Based on the families completed so far some preliminary analyses are possible, perhaps with some objective manipulating of the data. Up until 2006: 176 families, with 1,018 genera and 7,520 species have been treated. Since 2007: seven families, 95 genera and 506 species have been treated in four volumes, including Apocynaceae, in part (295 spp.) and Cucurbitaceae (121 spp.), and this data is yet to be incorporated into any analysis. The recent analyses of the limited data at the regional level have shown some interesting patterns of diversity, distributions, relationships and endemism (van Welzen 1997, Roos *et al.* 2004, van Welzen *et al.* 2005; van Welzen & Slik, 2009). They have suggested a new subdivision of the Malesian region, from two (West and East Malesia) to three (Sunda Shelf, Wallacea and Sahul Shelf), and also suggested the phytogeographic positions for Java and Sulawesi (van Balgooy, 1987; Roos *et al.*, 2004; van Welzen *et al.*, 2011). While past phytogeographical analyses using the genus have not found Wallace's Line to be a barrier for plant dispersals, it appears to be a significant barrier at species level (van Balgooy 1987; van Welzen *et al.* 2005).

All the recent analyses have confirmed the position of New Guinea as the richest and most endemic flora in the region (van Balgooy 1987; Roos *et al.* 2004; van Welzen *et al.* 2005, van Welzen & Slik 2009), followed by Borneo (Table 8). This is not surprising as both New Guinea and Borneo are the largest phytogeographic units in Malesia, thus conforming to the Island Biogeography theory (MacArthur & Wilson 1967), that suggests that there is a positive correlation between island size and number of species. However, New Guinea shows a significantly higher number of endemic species than most of the regions, and is in fact the only region with more endemic than non-endemic species.

The flora of New Guinea has received some preliminary analyses in the past or has been discussed in a more regional context (Lam 1934; van Steenis 1954; Good 1960; Heyligers 1972; Hoogland 1972; van Balgooy 1976; Hartley 1986). Even though the last most important floristic analysis was carried out almost 40 years ago (van Balgooy 1976), the conclusions reached then are still relevant today. Only the three more detailed and relevant analyses of the flora are discussed and compared here. There is no consensus in the number of families recognized by all three phytogeographic analyses of the flora (Good 1960; van Balgooy 1976; Hartley 1986). This is understandable as the number is dependent on which system of classification is followed, and also the fact that there is generally less agreement on the delimitations of families than genera, and this is best shown by the present unstable familial classification of the ferns.

Table 8. The total number of species, number of endemics and non-endemics per region; based on all families treated in Flora Malesiana Series 1 and the Orchid monographs (adapted from van Welzen & Slik 2009).

Region	Area (km²)	Total species	Non-endemics	Endemics	Endemism (%)
New Guinea	894,855	2766	1277	1489	54
Borneo	739,175	2613	1645	968	37
Sumatra	479,512	1988	1774	214	11
Philippines	290,235	1770	1288	482	27
Sulawesi	182,870	1169	1009	160	14
Peninsula Malaysia	132,604	2030	1767	263	13
Java	132,474	1296	1236	60	5
Lesser Sunda	98,625	871	828	43	5
Maluku	63,575	905	827	78	9

Good (1960) recognized about 200 families with indigenous genera and 1,348 angiosperm genera, while van Balgooy (1976) used 1,465 genera in 246 families in his analysis of the seed plants (angiosperms and gymnosperms). On the other hand Hartley's (1986) study was more narrowly focused on rainforest genera of seed plants. He analysed 716 genera to see if their distribution patterns differ from the rest of the flora, and also made a detailed analysis of the non-aurantoid Rutaceae in New Guinea. The broad distribution types of New Guinea spermatophyte genera are shown in Table 9. Asian and Australasian distribution types reflect the affinities of the New Guinea flora, and therefore, about 45-60% of the genera have dispersed into New Guinea from the west or northwest through Malesia while only about 10-15% showed southern or eastern (Australian and Pacific) origins, and 9-13 are New Guinea endemics or genera centred in there but with few species in the nearby regions. Good (1960) has pointed out that two important statistics of the New Guinea flora that we must find answers to are the total number of indigenous genera and the proportion of endemics amongst them. Good (1960) records 140 strictly endemic genera, while van Balgooy (1976) and Hartley (1986) recognized 98 and 38 genera respectively. The most recent listing of New Guinea endemic genera is that given by Johns (1995), who listed 86 genera. This figure will continue to be revised as genera are sunk into more widespread genera after monographic and phylogenetic studies of larger families. The number of newly described endemic genera has slowed down over the last three decades. However, despite all these changes at the genus level New Guinea's position as the richest and most endemic flora in the Malesian region will stand.

At present the only completed flora of any region within New Guinea is the four volume 'Alpine Flora of New Guinea,' which if synthesized may provide some insights into the characteristics of this rich flora (van Royen 1979-1983). This represents the single most important contribution to the documentation of the New Guinea flora. Volumes 2 - 4 documented the plants known to occur from 3,000 m altitude and above. A total of 1,116 species of vascular plants were treated, of which 963 are New Guinea endemics (86% endemism) (Figure 90). The alpine flora in New Guinea shows both Asian and Australasian relationships, and that species endemism is extremely high (Figure 90, Figure 91, Table 10). Van Balgooy (1976) identified 138 genera as belonging to montane zone (rarely seen below 1000 m altitude), and these show a slightly stronger Australian affinity than Asian (Figure 91).

Table 9. Broad distribution types of New Guinea seed producing (spermatophyte) genera from three recent phytogeographic analysis of the New Guinea flora.

Distribution	Number of spermatophyte genera (%)		
	Good (1960)	Van Balgooy (1976)	Hartley (1986)
Widespread	357 (27%)	403 (28%)	164 (23%)
Asian	663 (49%)	686 (47%)	413 (58%)
Australasia	188 (14%)	181 (12%)	74 (10%)
New Guinea endemic or centred	140 (10%)	195 (13%)	65 (9%)

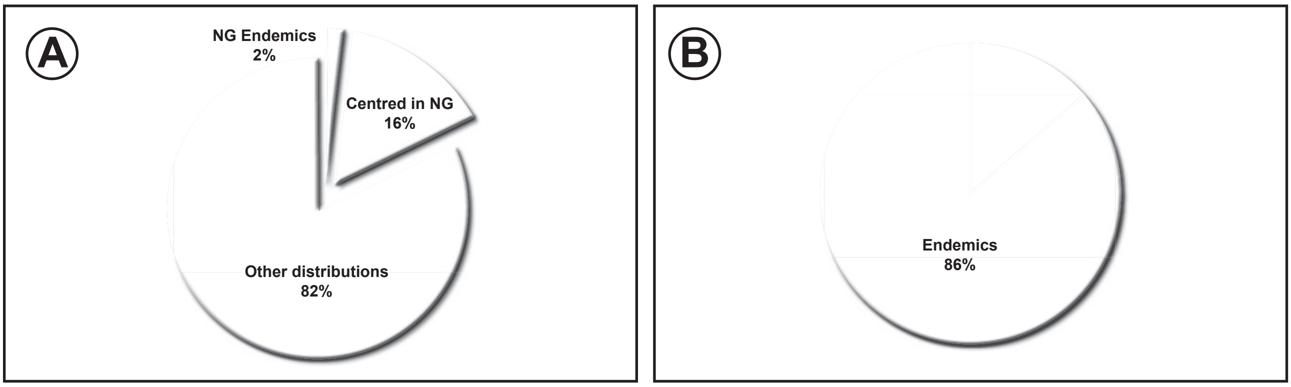


Figure 90. Endemism in New Guinea alpine flora. Endemic and New Guinea centred genera (A), endemic and non-endemic New Guinea species (B) (data source: van Royen 1979-1983).

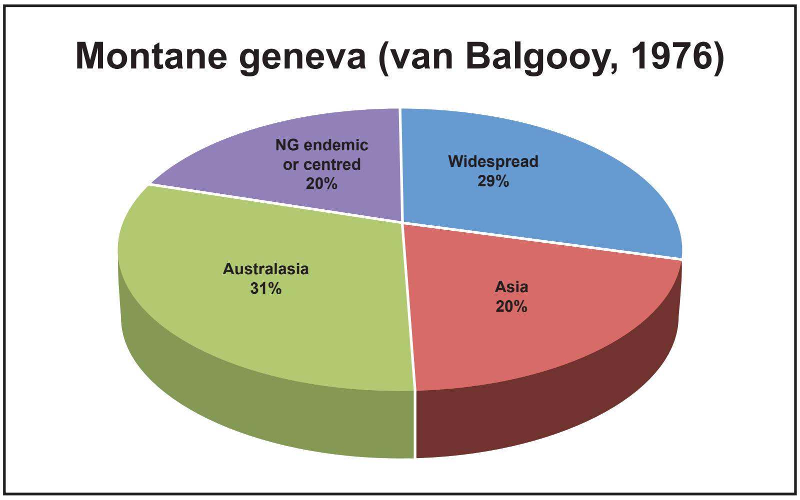


Figure 91. Relationships of the montane genera (adapted from van Balgooy (1976)).

Table 10. The top six most specious families in the alpine flora of New Guinea (van Royen, 1979-1983).

Family	Number of Genera	Total Species	Endemic Species	Endemism
Orchidaceae	26	250	248	99%
Ericaceae	6	140	138	99%
Asteraceae	21	100	86	86%
Poaceae	17	64	48	75%
Cyperaceae	9	42	5	12%
Rubiaceae	9	42	39	93%

Another rarely cited reference is the ‘Dictionary of the Genera and Families of Flowering Plants and Ferns’ (Höft 1992), in which Höft gave species estimates for all the genera recorded in Papuasia. Based on this estimate he gave a figure of 15,230 species for Papuasia, with 97 endemic genera (84 New Guinea endemics). Unfortunately, the number of species for New Guinea cannot be extracted from his figures, but New Guinea certainly represents about 80-90% of the Papuasian species. The 20 most specious families in Papuasia are listed in Table 11. The top six families are Orchidaceae, Rubiaceae, Fabacaeae (s.l (sensu lato)), Poaceae, Ericaeae and Euphorbiaceae, and these families (with 400+ species) contribute 5,470 species or 36% of total 15,279. Interestingly, Lowry (1998) found the four largest families in the New Caledonian flora (Myrtaceae, Rubiaceae, Orchidaceae, and Euphorbiaceae) to represent 27% of the total flowering plant flora (Morat 1993). Of the eleven most specious genera (100+ species, Table 12) in Papuasia, about half (45%) of their total 2,229 species belong to the two large orchid genera *Bulbophyllum* and *Dendrobium*.

Table 11. Families of vascular plants with 200 or more species in Papuasia (Höft 1992).

Family	Genera in Papuasia	Species in Papuasia	Genera in the World	Species in the World
Orchidaceae	150	2,806	795	17,500
Rubiaceae	73	838	637	10,700
Fabaceae (s.l.)	116	503	657	16,400
Poaceae	132	461	737	7,950
Ericaceae	6	436	103	3,350
Euphorbiaceae (s.l.)	52	426	326	7,750
Annonaceae	32	400	128	2,050
Apocynaceae (s.l.)	62	349	563	5,000
Arecaceae	40	314	207	2,675
Myrtaceae	28	308	121	3,850
Lauraceae	16	278	45	2,200
Thelypteridaceae	18	261	30	900
Cyperaceae	29	243	115	3,600
Melastomataceae	22	235	215	4,750
Araliaceae	15	225	58	800
Aspleniaceae (s.l.)	33	224	78	2,700
Urticaceae	22	222	52	1,050
Asteraceae	69	217	1317	21,000
Gesneriaceae	13	208	146	2,400
Zingiberaceae	16	207	53	1,200

Table 12. Genera with 100 or more species in Papuasia (Höft 1992), with comments from recent reliable sources.

Family	Genus	Total Species	Species in Papuasia	Comments
Orchidaceae	*Bulbophyllum*	1200	500	Schuiteman & de Vogel (2007) suggest 600 spp.
Orchidaceae	*Dendrobium*	900	500	Schuiteman & de Vogel (2007) suggest 400 spp.
Ericaceae	*Vaccinium*	450	175	Craven (2007) suggest c.130 spp.
Araliaceae	*Schefflera*	800	170	
Ericaceae	*Rhododendron*	850	155	Craven (2007) suggest c. 150 spp.
Moraceae	*Ficus*	800	138	Berg & Corner (2005), 216 species
Myrtaceae	*Syzygium (s.l.)*	500	138	Craven (2007) suggest 200+ spp., broader sense.
Rubiaceae	*Psychotria*	2000	124	Sohmer (1988) suggested 200-300 species.
Gesneriaceae	*Cyrtandra*	350	121	
Orchidaceae	*Phreatia*	190	108	Schuiteman & de Vogel (2007) suggest 130 spp.
Piperaceae	*Piper*	1000	100	

To give an example of the patterns of diversity in a large and specious family in New Guinea, a preliminary analysis of the Rubiaceae, the second largest family in New Guinea is described (Gideon, unpublished data). About 60% of the genera are Paleotropical (35% are actually Indo-Pacific), and 9% are endemic (a single Solomon Islands endemic). About 84% of the New Guinea species are endemics (Figure 92). The New Guinean Rubiaceae shows overwhelmingly 'Asian' affinities and a negligible Australasian relationship. These figures are not likely to change significantly when the family has been fully treated in a modern revisionary study.

Probably the best way to assess regional patterns of biodiversity and endemism is by analysing and synthesizing data held in various forms, such as taxonomic revisions and properly identified and geo-referenced herbarium specimens, rather than counting species in plots. However, both approaches provide both unique as well as comparative information, and they complement each other. There are now many examples of botanists using taxonomic or specimen data to detect centres of species richness and endemism (e.g. van Welzen 1997; Heads 2001; Crisp *et al.* 2001; Roos *et al.* 2004; Vollering *et al.* 2015). Even though New Guinea has long been recognised as an important centre of plant diversity, very few field studies have been carried out to assess its diversity, forest structure and other forest variables (Paijmans 1970; Kiapranis 1990; Oatham & Beehler 1997; Reich 1998; Wright *et al.* 1997; Balun *et al.* 2000; Polak 2000; van Heist *et al.* 2010; Whitfeld *et al.* 2014). Unfortunately, their results are not easily compared because of differences in objectives, sample sizes, variables measured, etc. Most of the studies measured species diversity and abundance in various forest types, while a few looked at species diversity along altitudinal gradient or changes in species diversity, composition, structure in forest succession (van Heist *et al.* 2010; Whitfeld *et al.* 2014). Recently, the first 50 ha permanent plot in New Guinea has been established at Wanang, Madang Province (see Chapter 4). This plot will contribute valuable information on New Guinea's lowland flora, and also provide the basis for comparisons with other tropical areas.

Species richness patterns throughout New Guinea and nearby archipelagos are quite complex and only a few studies on species diversity along altitudinal gradients have been undertaken (Balun *et al.* 2000; Forster 1997; Kulang *et al.* 1997; Takeuchi & Wiakabu 1997). Aside from Balun *et al.* (2000), the other studies are unpublished and cited in Takeuchi and Golman (2001). Balun *et al.* (2000) conducted a transect study on New Britain Island from sea level to 1,600 m altitude, and enumerated all vascular plants and epiphytes up to 10m above ground in 0.2 ha plots at every 200 m altitude. They found that plant species diversity peaked between 600-800 m altitudes (150 species at 600 m), and this compares well to Forster's (1997) transect from southern New Ireland which peaked at 750 m. Another similar study on the mainland at Hagahai area of Madang Province found that species diversity peaked slightly higher, between 800 and 1,000 m elevation with 281 species (Kulang *et al.* 1997). These few studies indicate that the lowland-montane transition zone appears to be the region's centre of species richness. There is obvious variation (600-1,200 m) in the elevations of beta diversity maxima, obviously influenced by local factors, including the 'Massernerhebung effect.' The ecotone needs to be studied more intensively for both flora and fauna so that New Guinea's centres of diversity and endemism can be identified. Generally, species richness in New Guinea forests appear to fall within the ranges documented across the tropical zone.

As the flora of New Guinea continues to be explored and new species described, the patterns of diversity, distribution and endemism will slowly emerge. New species are discovered and described every year, either from recent collections or specimens stored in world herbaria. A recent survey of new species described from New Guinea in a decade (1998-2008) reported 218 new plant species, and 100 of these were orchid species (WWF Report 2011). Obviously, many species were not counted and the average figure could be as high 250 species per decade. The figures for plants and animals were actually almost three times as many as those from Borneo for the same period, an island of similar size, climate and geological history.

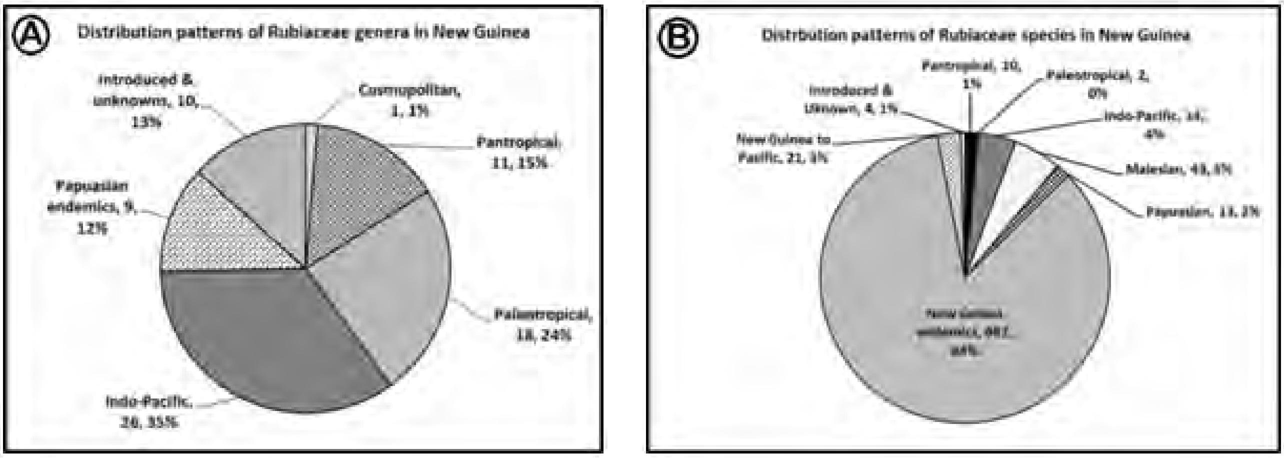


Figure 92. Genera (A) and species (B) distribution patterns in New Guinea Rubiaceae.

Figure 93. *Hoya* sp.nov. (Asclepiadaceae), most likely an undescribed species from Cape Rodney Area, Central Province.

Figure 94. *Cyrtandra* sp. (Gesneriaceae) and *Begonia* sp. (Begoniaceae), from New Britain Island (Vidiro Gei photographs).

History of botanical exploration

Botanical Exploration and Growth of Local Institutions

New Guinea is one of the last botanical frontiers to be explored for economic and scientific purposes. History of biological explorations of New Guinea has been well covered by various authors (van Steenis-Kruseman 1950; van Royen 1979; Frodin and Gressitt, 1982; Frodin 1990a, b, 2007; and Takeuchi, 2007), and a summary can be read in Chapter 5.

The most significant plant collector in New Guinea was the Queenslander Leonard J. Brass, whose contributions to New Guinea botany is only rivalled by Wayne Takeuchi (see below). Leonard J. Brass first arrived in 1925 to collect plants for the Arnold Arboretum of Harvard University, and over the next 40 years he was an extraordinarily prolific collector (Perry 1971, The Arnold Arboretum 2012). He was hired as botanist for the first Archbold Expedition in 1933/1934, and continued on for all subsequent expeditions. Dr Lily May Perry had the task of working up the Brass collections, and described his botanical collections as "well chosen, ample and beautifully prepared, and his collection data were both extensive and meticulous" (Perry 1971). Botanical results of the Archbold Expeditions were mostly published by Elmer Merrill and Lily May Perry in the series "Plantae Papuanae Archboldianae" (Perry 1971, The Arnold Arboretum 2012). Over 180 species and genera of plants were named after Leonard Brass. In December 1985 the writer had the honour of meeting Dr LM Perry in person at Hingham, Massachusetts, and she was then 90 years old. It was an honour to be the only New Guinean to have personally met Dr Perry, one of the most prolific describers of New Guinea plants, a place she knew so well but never visited.

During World War II several Australian, American and Japanese soldiers collected plant specimens in New Guinea, but most of that material was lost. In fact botanical work by servicemen was insignificant compared to collections of insects and other smaller organisms that could be easily transported. The most important botanical collections were those assembled by the Australian armed forces. In 1944 a forestry unit was established under the command of J.B. McAdam (Frodin & Gressitt 1982). Faced with the reality that most forest trees in New Guinea were poorly known, McAdam directed that collections of herbarium material and wood samples be assembled. These collections were initiated at Lae by C.T. White and H. Dadswell, and carried forward by Lindsay Smith and other servicemen. Hence, the birth of the NGF (New Guinea Forces) botanical collection number series. At the end of the war some 2,000 plant specimens were left in Lae for the colonial administration to develop further as the Papua New Guinea National Herbarium (Frodin & Gressitt 1982).

When J.B. McAdam was appointed as the first post-war Director of Forests, a Forest Botanist position was created. The person was to be based in Lae, and was to take charge of the botanical collections started during the war and develop it further into a National Herbarium. John Womersley was appointed the first Forest Botanist in 1946, and he would remain the chief government botanist until his retirement in 1975 (Frodin & Gressitt 1982). Under Womersley's direction, a Division of Botany was established to further develop the herbarium collections and later a Botanic Garden for living collections was added. The Herbarium, then famously known as the Lae Herbarium with the acronym LAE, changed its status to that of the PNG National Herbarium. Upon his retirement in 1975 the herbarium had about 260,000 collections. Most of these came from major expeditions organised by the Division or in association with forestry surveys. In the early years the Division concentrated on timber trees, but eventually extended to cover all higher plants. To date there are about 400,000 specimens, and by far the largest botanical collection in whole of New Guinea (Takeuchi, 2007). Foreign botanists who were based at the Lae Herbarium and contributed important collections included J.S. Womersley, P. van Royen, M.J. Coode, A.G. Floyd, E.E. Henty, A.N. Miller, J. Vandenberg, J. Buderus, D.B. Foreman, W.R. Barker, C.E. Ridsdale, A.N. Gillison, P.F. Stevens, R.J. Johns, D.G. Frodin, N. Clunie, B.J. Conn, S.H. Sohmer, and J.R. Croft, the last foreign botanist to leave LAE in 1987. Important national collectors included M. Galore, P. Katik, G. Larivita, Y. Lelean, A. Vinas, J. Wiakabu, M. Benjamin, K. Kerenga, K. Damas, O. Gideon, R. Kiapranis, R. Banka, B. Bau, and many others who only stayed briefly. Benjamin, Kerenga, Damas and Gideon were the first nationals to be recruited in the late 1970s to be trained further as plant taxonomists, and to date only Damas and Gideon continue to serve as botanists. Botanical collecting intensity by the PNG National Herbarium began to decline after independence in1975. This decline is attributed to economic and political reasons rather than scientific (Frodin 1990b). During the late 70s and the 80s there was at least one major expedition every year, and with additional specialist collecting with visiting botanists.

Several foreign botanists made extended stays in New Guinea, and one that stayed the longest was Wayne Takeuchi, originally from Bishop Museum, Hawaii. He first arrived in LAE in 1988, and would remain for over 23 years collecting firstly for Bishop Museum, then for Botanical Research Institute of Texas, and before his departure for the Harvard University Herbaria. His well-chosen and prepared specimens, with extensive field notes and many duplicates are now distributed in major herbaria around the world. He is certainly the only botanist to rival L.J. Brass's collections, both in number and quality of specimens. He probably collected in the vicinity of 23,000 specimens from New Guinea, mostly from Papua New Guinea but also from Papua in the last few years.

Other botanical centres in New Guinea include the Forestry Herbarium started in 1952 by the Dutch at Hollandia (now Jayapura), but later moved to Manokwari in 1958. Collections were made under the BW (Boswezen) series, which by 1962 contained about 15,000 specimens (Frodin 1990b). Dutch botanists and foresters stationed at Manokwari (MAN) included C. Kalkman, W. Vink, C. Versteegh, J.F.U. Zieck, F.A.W. Schram and C. Koster, and assisted by Papuans Peter and Gerrit Iwanggin (Frodin & Gressitt 1982). The most prominent amongst the first crop of Papuan botanists include Rudi Maturbongs and Charlie Heatubun, both making important contributions in palm taxonomy. The last major expedition under the Dutch administration was to the Star Mountains from April to August 1959, and aside from zoologists, botanists included C. Kalkman, B.O. van Zanten and J.J.F.E. de Wilde. Results of these collections appeared in Nova Guinea and elsewhere. When the Dutch left New Guinea in 1963 botanical collecting in west New Guinea came to a stop. Current holdings are estimated to be about 30,000 mounted specimens (Takeuchi 2007).

Many individuals, both local residents and visitors, have made important contributions to the growth of plant collections from New Guinea. Many resident missionaries collected plants and contributed to science in many ways. One remarkable resident plant collector was Rev. Norman E.G. Cruttwell, who was sent to New Guinea in 1946 as a missionary by the Anglican Church and was based at Dogura, Milne Bay Province (Frodin & Gressitt 1982). He was an excellent botanist and roamed over many of Papua New Guinea's south-eastern mountains such as Mount Simpson (1947), Mount Dayman, (1951), and Mount Aniata (1959), Mount Suckling with the joint Lae/Leiden expedition (1972) (Frodin & Gressitt 1982). In 1976 he transferred to Goroka and continued his botanical interests in the Highlands of Papua New Guinea.

The establishment of tertiary institutions in Papua New Guinea in the 1960's and 1970's saw the development of small, and more specialised teaching and research herbaria in Port Moresby (UPNG), Bulolo (Forestry College), and Wau (Wau Ecology Institute). Important collectors at Bulolo were J.J. Havel, H. Streinmann, A. Kairo, R.J. Johns, A. Hay, A. Bellamy and L. Balun, and at UPNG were R. Robbins, M. Pulsford, A. Gebo, D.G. Frodin, J. Powell, K. Naoni, C. Huxley, H.C. Hopkins, M. Kuduk, A. Vinas, P. Piskaut , O. Gideon and J. Gagul (Frodin & Gressitt 1982). Both UPNG and Bulolo herbaria are estimated to contain just over 20,000 mounted specimens. While these small institutions did not undertake extensive botanical collecting like the Division of Botany in Lae, altogether they have made important contributions to the botanical knowledge of New Guinea. The contrast between Papua New Guinea and the Indonesian Provinces is clearly reflected in the differing status of the local scientific institutions.

Figure 95. *Riedeia* sp. nov. (Zingiberaceae), an undescribed epiphytic species from Woodlark Island, Milne Bay Province. The genus is centred in New Guinea with about 90% of its > 60 species found there.

Some overseas institutions have made significant contributions, particularly Australian institutions like CSIRO with its Land Resources and Regional Surveys Division and the Research School of Pacific Studies of the Australian National University (ANU). Important CSIRO plant collectors included R.D. Hoogland, P. Darbyshire, L. Craven, R. Pullen, R. Schodde, P.C. Heyligers, K. Paijmans, A. Kanis and J.C. Saunders. T.G. Hartley carried out a phytochemical survey for the Chemical Survey Division, and collected over 3,000 specimens. Under the direction of Professor Donald Walker at ANU, a number of students (e.g. J. Flenley, G.S. Hope, J.W. Powell, R.T. Corlett, R.J. Hnatiuk, J.M.B. Smith, D.N. McVean, S. Garrett-Jones) carried out important research on New Guinea's paleoclimate and paleoecology from the 1960s to 1980s. Most of them collected important specimen vouchers which are deposited at ANU (GAUBA), the Australian National Herbarium (CANB), and the Papua New Guinea National Herbarium (LAE). A number of major herbaria overseas conducted joint expeditions with LAE, especially Leiden (L), Kew (K), and Arnold Arboretum of Harvard University (A and GH). Numerous individuals also made their mark, including several cryptogamists (e.g. Koponnen, Streimann, Norris, etc.). During the last two decades general collecting throughout New Guinea declined considerably, and any recent efforts have been mainly specialist collecting.

The Leiden Herbarium (later Netherlands National Herbarium, and now Netherlands centre for Biodiversity Naturalis) was the main European institution active in New Guinea after World War II (Frodin & Gressitt 1982). It organised two important expeditions to west New Guinea around Vogelkop Peninsula in 1954/1955 (botanist: P. van Royen) and in 1961 (botanists: P. van Royen and H. Sleumer). In Papua New Guinea they conducted joint expeditions supported by the Lae Herbarium, and several local based botanists also participated. These included the 1966 expedition to Doma Peaks and Telefomin (botanists: C. Kalkman and W. Vink), 1972 to the Mt. Suckling Complex (botanist: J.F. Veldkamp), 1973 to Mt. Bosavi (botanist: M. Jacobs), and ending with the 1975 expedition to the eastern Star Mountains (botanists: J.F. Veldkamp and A. Touw) (Frodin & Gressitt, 1982). Kew Herbarium of the Royal Botanic Gardens, London made only minor contributions to New Guinea botany until the 1998 to 2000 programme in the P.T. Freeport mining concession area, which concentrated more on the alpine and subalpine flora of Mt. Jaya. In the two year programme some 38 botanists and other specialists participated, collecting about 5,000 specimens with many duplicates (Utteridge *et al.* 2006).

Botanical exploration of New Guinea has been very uneven, both between the eastern half (PNG) and the western half (Indonesian Papua), but also within each country. Takeuchi (2007) illustrated the difference between the two halves of the island, finding sampling intensity in PNG was three times better than the Indonesian half of the island. The holdings of the PNG National Herbarium stands at about 400,000 specimens compared to the modest 30,000 in Papua. There is also considerable disparity within the borders of the two political halves, which is best shown in Papua New Guinea (Figure 96, Takeuchi & Golman 2001)). Almost half of these collections came from the Momase region, and in fact 28% came from Morobe Province alone where the National Herbarium is located. Certain Provinces are clearly poorly represented (Gulf, Northern, New Ireland, East New Britain, Manus, Enga), and they should be targeted in future botanical explorations to fill the gaps (Takeuchi & Golman 2001).

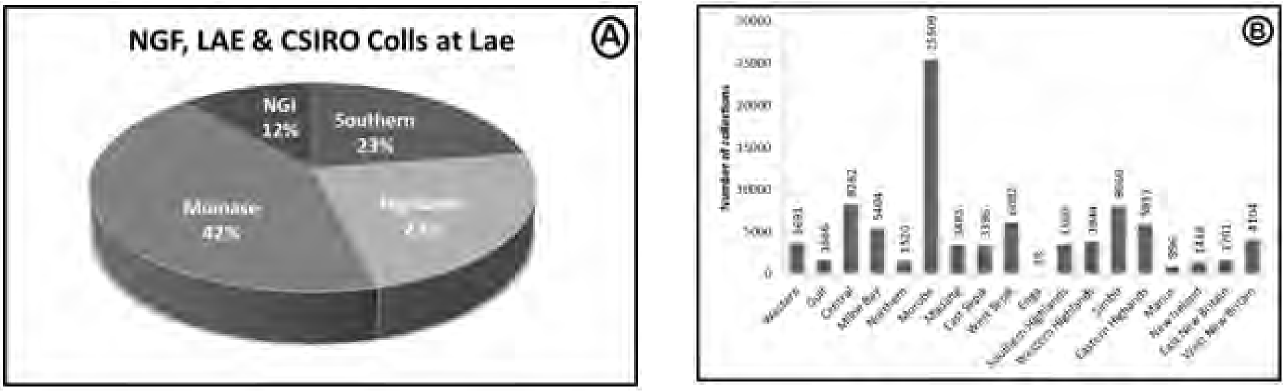


Figure 96. There is a clear disparity in collections under the NGF, LAE and CSIRO number series held by the PNG National Herbarium, arranged by region (a) and by Province (b) . Momase (Morobe, Madang, East and West Sepik), Highlands (all Highlands Provinces), Southern (Western, Gulf, Central, Milne Bay and Northern), and New Guinea Islands (NGI -East and West New Britain, New Ireland and Manus). (Adapted from Takeuchi & Golman 2001).

Gaps in floristic exploration have also been identified in the Indonesian half of New Guinea (Prance 1977; Campbell 1989; Stevens 1989; Supriatna *et al.* 1999), but the situation is much worse than in Papua New Guinea. Current botanical information for the West Papuan provinces comes from only a few areas, such as the Vogelkop Peninsula, Cyclop Mountains, Idenburg River, Mts Jaya and Trikora, Lake Habbema, Wissel Lakes, and Freeport-Timika area. However, except for possibly Mt. Jaya because of the recent publication of a guide to its flora (Johns *et al*. 2006), none of the other areas come anywhere close to well-known areas in Papua New Guinea, such as Mt. Wilhelm, Wau-Bulolo area, Lae-Markham, Sogeri, Brown River, (Takeuchi 2007).

Intensive collecting invariably produces a rich specimen base for studies in systematics, ecology, biogeography, and other disciplines. A good flora must be based on extensive and well prepared specimens from throughout the region. Stevens (1989) estimates that some 450,000 plant specimens from New Guinea exist in world herbaria, which could provide the basis for a flora of New Guinea project. Collecting density index or CDI (collections/100 km^2) is an important measure of how well a flora is known. In 1950 the CDI for New Guinea was 12 (higher in Papua New Guinea) (Frodin 1990b), compared to 62 for Philippines and 145 for Malay Peninsula. By 1972 it was 26 in New Guinea (much higher in Papua New Guinea), 69 in Philippines and 175 in Malay Peninsula. The CDI for Papua New Guinea at 1989 stood at 46, but the Solomon Islands and Papua were much less well covered (Frodin 1990b). With the recent botanical activities the Papua New Guinea CDI is close to 50 (Takeuchi 2007), but for the Indonesia Provinces they still lag behind at 20 (Supriatna *et al*. 1999). While New Guinea is still behind the other regions of Malesian, progress is being made, especially in Papua New Guinea. Prance & Campbell (1988) have identified New Guinea as a 'World priority for future work.'

Conclusion

New Guinea is clearly one of the most exciting regions of the World in which to study plant biogeography, mainly because of its strategic position. However, this interesting flora remains poorly known and at present we can only estimate its size and speculate on its relationships based on expert opinion and limited data. Despite some progress made over the last three decades, major gaps still exist in our knowledge of the ecology, distribution and evolution of the New Guinean flora. The increasing use of molecular technologies and Geographic Information Systems (GIS) software are helping us to understand patterns of diversity and biogeography, and the broad scale mapping of species richness and endemism. Some recent studies have demonstrated the value of properly identified specimen data in detecting centres of species richness and endemism, and mapping with appropriate indices (Crisp *et al*. 2001; Vollering *et al*. 2015).

With its diversity of landforms and many unique habitats, speciation events have contributed to the high diversity and endemism of the flora, making New Guinea a special place. However, without proper conservation planning habitat losses, mainly due to human activities, may result in major species loses of this rich and unique flora. The lowland rain forests have been subjected to selective logging over the past 50 years, with forest clearing for agriculture and mining activities. This is mainly fuelled by the insatiable appetite for natural resources by developed and fast developing countries. Furthermore, unsustainable population growth in certain parts of the region, as well as the slash and burn agricultural systems practiced throughout, are increasingly becoming major threats to this rich biodiversity. Shearman *et al*. (2008) have shown that logging and agriculture are major threats to biodiversity in Papua New Guinea through forest conversion.

To date, the knowledge of New Guinea's rich biodiversity is still patchy and imprecise, and much of the current conservation efforts are not based on reliable scientific data. Our rich biodiversity is our inherited wealth, and a detailed knowledge of the extent and condition of this resource is essential for its wise and sustainable exploitation. Both Papua New Guinea and Indonesia appear to ignore the obvious seriousness of the threats to New Guinea's rich biodiversity. The current "business as usual" attitude will fall short of meeting conservation challenges, especially under international conventions such as CBD, CITES, etc. Both countries need to reform their management of biodiversity, review existing policies and legislations and implement effective policies that meet existing and emerging threats to biodiversity. Identification of key areas for conservation must be based on hard scientific data, and to achieve this both countries need to take stock of resources and institutions needed to meet conservation needs and challenges. Scientific institutions remain poor in both countries and human capacity has remained stagnant, even though universities in New Guinea have been awarding BSc degrees for over 40 years. There are glaring disparities between Papua New Guinea and the Indonesian half of the island, from collecting intensities to development of local botanical centres (Takeuchi 2007). If appropriate actions are taken by responsible leaders in both countries, in conjunction with scientists and the conservation community, there is a good chance that this remarkable botanical diversity can be protected to some degree. However, failure to do so may condemn this rich and unique flora to the same irreversible fate of so many other tropical floras, such as those of the Philippines, Indonesia and Thailand.

Nepenthes sp. Kamiali

Chapter 8

Ongoing discovery of mammal diversity in New Guinea

Ken Aplin

Ken Aplin has been visiting PNG and working on its mammal fauna since 1981. In recent years he has been involved in numerous environmental assessment projects for resource developers. He is a Research Associate of the Division of Mammals of the U.S. National Museum, Smithsonian Institution.

New Guinea is one of a relatively small number of places around the world where new species of mammals are still discovered on a regular basis – other such places include the island nation of Indonesia to the west, and remote parts of South America, Southeast Asia and Africa. In each of these places, new mammals are discovered in one of three main ways. The first satisfies the classic notion of new species discovery – an entirely new mammal species captured for the first time during a period of field work in a remote or poorly sampled location. The second comes from work on existing museum collections – that moment when a specimen collected sometime in the past is re-examined in the light of new information and recognized as belonging to a new species. The third is during surveys of genetic diversity – these often reveal so-called 'cryptic' species, one that differs in very subtle morphological features from related forms but is on its own evolutionary path. Recent and ongoing studies of Papua New Guinean mammals present examples of all three kinds of discovery, with many more likely to occur in the near future.

In the past decade 15 new species of mammals have been described from New Guinea. These comprise 14 species of rodents and one insectivorous bat. In addition, two new genera have been erected for distinctive groups of New Guinean rodents. The most recently described marsupials from New Guinea were named as recently as 2004 – the Arfak Pigmy Bandicoot (*Microperoryctes aplini*) and the Blue-eyed Spotted Cuscus (*Spilocuscus wilsoni*). Three new kinds of monotreme (primitive egg-laying mammals that are found only in Australia and New Guinea) were named as recently as 1998 – Attenborough's Long-Beaked Echinda (*Zaglossus attenboroughi*) and two new subspecies of the Eastern Long-beaked Echidna (*Z. bartoni diamondi* and *Z. b. smeenki*).

Virtually all of the recently described New Guinean mammals were detected through careful study of specimens held in various museum collections around the world. This is a great testimony to the value of these museum collections and also an incentive to continue building these collections into the future. Perhaps the most remarkable of these discoveries were two highly distinctive species of shrew mice that were erected in the new genus *Mirzamys* – both species had been collected several decades earlier but the specimens had sat unrecognized in museum collections. A second new genus, Brassomys, was proposed in 2009 for a small rodent formerly known as *Melomys albidens*. This species was named in 1951 and is still known only from three specimens collected in moss forest around Lake Habbema, in the high mountains of Indonesian Papua.

Figure 97. This tiny member of the fruit bat family is probably the most abundant mammal in New Guinea montane forests. It is without a scientific name because its distinctive features such as thicker fur and shorter snout were thought to reflect adaptations to colder conditions. Genetic studies demonstrate that it is a distinct species that evolved in the central mountains of New Guinea.
Photo credit: S.J. Richards

The last decade has also seen a resurgence of field work in New Guinea. Some of this new effort has been sponsored by non-government organizations (NGO) with an explicit interest in biological discovery and conservation. However, a larger share has been linked to resource development projects for which environmental assessments are a necessary step in the process of gaining project approvals. Since much of this recent fieldwork has taken place in some of the most remote and biologically unexplored parts of Melanesia, the discovery of entirely new kinds of mammals should not come as too big a surprise. Even so, a fieldtrip in 2009 to the mountainous interior of East New Britain produced a surprising number of unexpected mammals. Five species of native rodents were encountered on this trip, three of them being undescribed species. Subsequent work in museum collections revealed that two of the species had been collected previously on New Britain but were wrongly classified. However, the third species, a beautiful soft-furred tree mouse captured in moss forest at the highest elevation camp site, turns out to be an entirely new discovery – and not only an undescribed species but a member of a yet another new genus. The formal description of this species is currently underway. Other recent discoveries in the field include a third species of *Mirzamys*, this time from a remote high altitude locality in Hela Province, and a distinctive new species of *Rattus* from the same general area.

Two entirely new species of bats – members of the genera *Nyctimene* and *Hipposideros* – were encountered in 2014 during an NGO sponsored survey to the Admiralty and St Matthias island groups to the north of Papua New Guinea. In addition, new material was obtained that will allow scientific description of several other species including a very distinctive flying fox that was collected on Emirau Island in the St Matthias Group in 1944. Other bat species, at least some of them very likely new to science, were detected but not captured during this survey. The evidence for these species is in the form of distinctive echolocation calls recorded on 'bat detectors' that were set up to monitor insectivorous bat activity. Now that the presence of these species is known, further effort using more specific capture methods can be applied by future survey teams.

Figure 98. A striped possum (genus *Dactylopsila*) captured in the foothills of the Muller Range in 2009. Even some of the most distinctive and spectacular New Guinean mammals still harbor unrecognized diversity. At least two species, probably more, are currently lumped together as the Common Striped Possum, *Dactylopsila 'trivirgata'*. *Photo credit: S.J. Richards*

Figure 99. A long-footed tree mouse (genus *Lorentizmys*) from the upper Strickland catchment. This genus is one of the earliest branches of rodent evolution in New Guinea and it includes some of the smallest rodents in Melanesia today. Although only one species is currently recognized, new studies using genetics as well as the traditional skulls and teeth hint at a far higher diversity. Many species are known from only a few, widely scattered localities. *Photo credit: S.J. Richards*

Figure 100. New Guinea's insectivorous bat fauna is already well known for its richness and variety. However, the true diversity is badly underestimated for many groups. One of the most confusing groups are the Bent-winged Bats (genus *Miniopterus*; the species illustrated here comes from the Upper Strickland catchment). Members of this genus occur throughout the Old World but they are notoriously conservative in body form. Detailed studies using genetics and their echolocation call patterns are now underway for New Guinea and many new species are anticipated. *Photo credit: M. Sale*

Figure 101. The Pen-tailed possums (genus *Distoechurus*) belong to an ancient family of marsupials that probably evolved in Australia. Although all living populations are quite similar in size and general patterning, they show more genetic diversity than expected of a single species. A detailed morphological study of the genus has never been carried out. *Photo credit: S.J. Richards*

Figure 102. Much plant and animal speciation in New Guinea has occurred in response to the formation of the central mountain chain over the past 4-5 million years. Many mammals show patterns of altitudinal replacement, with each of a series of ecologically similar species confined to a particular elevational range. The Unstriped Tube-node Bats (genus *Paranyctimene*) shows this kind of pattern but several of the species remain unnamed. *Photo credit: S.J. Richards*

Figure 103. The flying foxes (genus *Pteropus*) have dispersed more widely through the Melanesian region than any other group of mammals and this has lead to much local speciation on small, remote islands. This highly distinctive species from Mussau and Emirau Island in New Ireland Province was first collected at the close of World War II but it has remained undescribed. New material collected in 2014 will facilitate its description and this process will initiate consideration of its conservation needs. *Photo credit: K. Aplin*

Figure 104. Owls and other predators often leave the remains of their prey behind in caves. These represent a bonanza for a scientist who can do a faunal survey without having to set a single trap. Analysis of cave remains has revealed the existence of several mysterious New Guinea mammals that are not yet represented in any museum collection. *Photo credit: S. Venter.*

Even more tantalizing are new discoveries where the only evidence for a new species is some bones or teeth found in a cave or rockshelter where an owl or other predator has discarded the remains of its prey. One example is a skull of *Brassomys* collected in 2014 from an owl roost at the eastern end of the Star Mountains. This provided the first evidence of *Brassomys* in Papua New Guinea but whether or not it belongs to *B. albidens* or to a second, undescribed species of the genus cannot be decided until a living animal becomes available for study. Similarly enigmatic are the remains of two different kinds of small water rat that are represented in owl roost remains from rugged limestone country in the hinterland of the Gulf of Papua. Both are almost certainly unnamed species and the hunt is on to capture living animals. Careful study of owl roost remains represents a powerful tool for detecting some of the rarest and most elusive of all New Guinean mammals.

Collection of blood and other tissue samples with a view to genetic studies of New Guinean mammals commenced in 1981. However, it was not until fairly recently that methods and technologies existed to allow broad-scale biodiversity screening of these samples. Thus far, genetic surveys have been conducted for only a small number of genera of New Guinean mammals. One recent study of New Guinean *Rattus*, a notoriously difficult group in which to identify species, revealed several potentially undescribed species, especially within the montane fauna. In addition, this study suggested that some of the more recently evolved species of *Rattus* are still capable of occasional interbreeding – this can blur distinctions and lead to underestimation of diversity. Similar complexity is likely to be present in many other groups of New Guinean mammals and genetic analyses may be the only means of determining the true pattern of diversity. Fortunately, methods for the analysis of gene flow between populations are developing fast, thereby making it relatively straightforward to trace history of hybrid interactions. Yet another exciting development is the increasing ease of recovering genetic information from museum specimens and even from bones and teeth from cave deposits. The integration of these different genetic methods should allow for rapid inroads to be made into the backlog of available samples, leading to much improved estimates of species diversity even among the most vexatious groups.

All in all, with the combination of ongoing field surveys, continued studies of existing museum, and the new emphasis and power of genetic analyses, it is possible to predict a steady rise in the recognition of new species of mammals over the next decade.

Table 13. New species of mammals described from New Guinea over the past 10 years.

Genus	Species	Reference	Year	Common name
Coccymys	*kirrhae*	Musser and Lunde	2009	Tawny Coccymys
Leptomys	*arfakiensis*	Musser, Helgen & Lunde	2008	Arfak Leptomys
Leptomys	*paulus*	Musser, Helgen & Lunde	2008	
Microhydromys	*argenteus*	Helgen, Leary and Aplin	2010	Southern Groove-toothed Shrew Mouse
Mirzamys	*louisiae*	Helgen and Helgen	2009	Mirza's western moss rat
Mirzamys	*norahae*	Helgen and Helgen	2009	Mirza's eastern moss rat
Pseudohydromys	*berniceae*	Helgen and Helgen	2009	Bishop moss-mouse
Pseudohydromys	*carlae*	Helgen and Helgen	2009	Huon small-toothed moss-mouse
Pseudohydromys	*eleanorae*	Helgen and Helgen	2009	Laurie's moss-mouse
Pseudohydromys	*germani*	Helgen and Helgen	2009	German's One-toothed Moss Mouse
Pseudohydromys	*patriciae*	Helgen and Helgen	2009	Woolley's Moss-mouse
Pseudohydromys	*pumehumae*	Helgen and Helgen	2009	Southern small-toothed moss-mouse
Pseudohydromys	*sandrae*	Helgen and Helgen	2009	White-bellied Moss-mouse
Nyctophilus	*shirleyae*	Parnaby	2009	Mt Missim Big-eared Bat

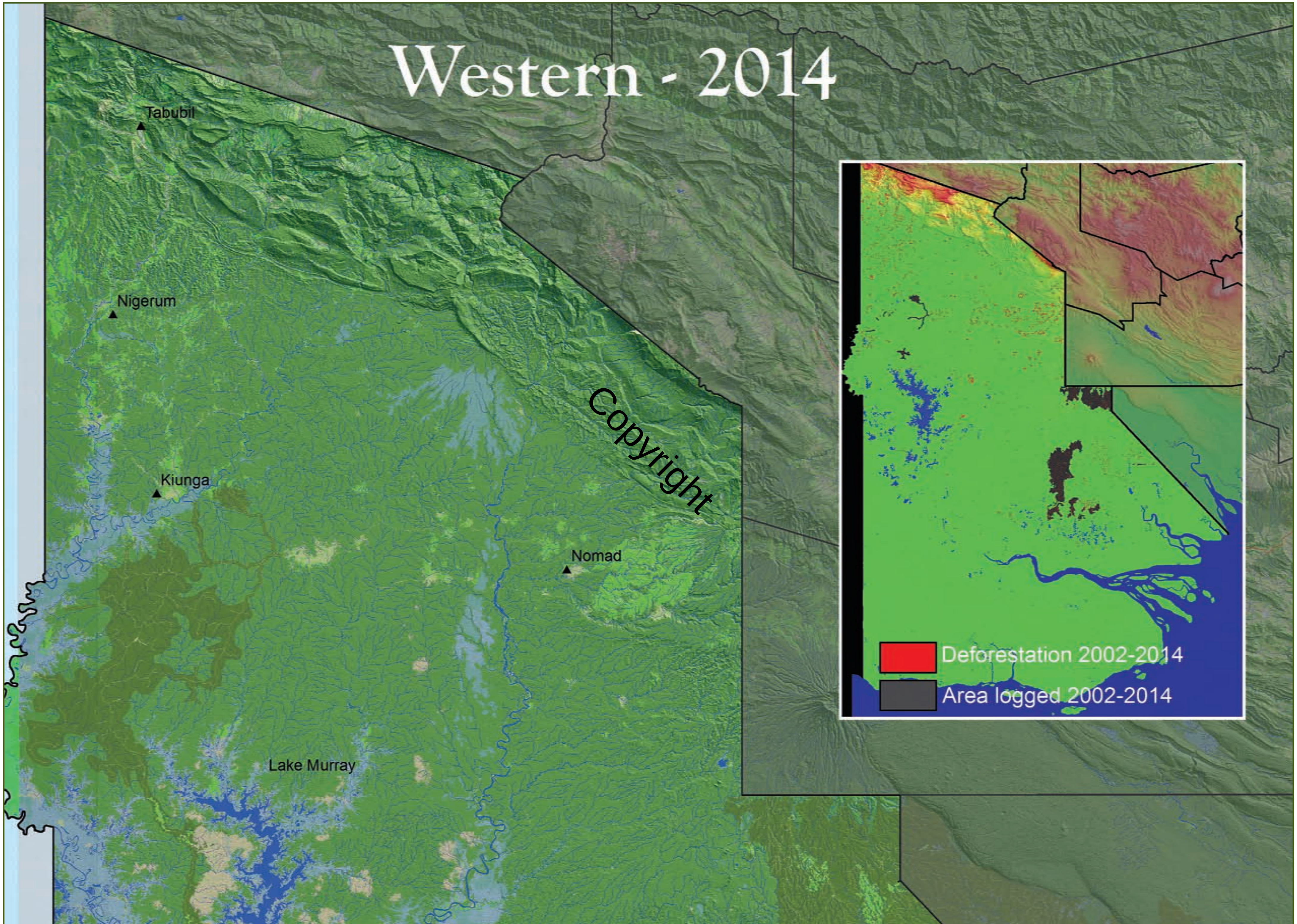
Chapter 9

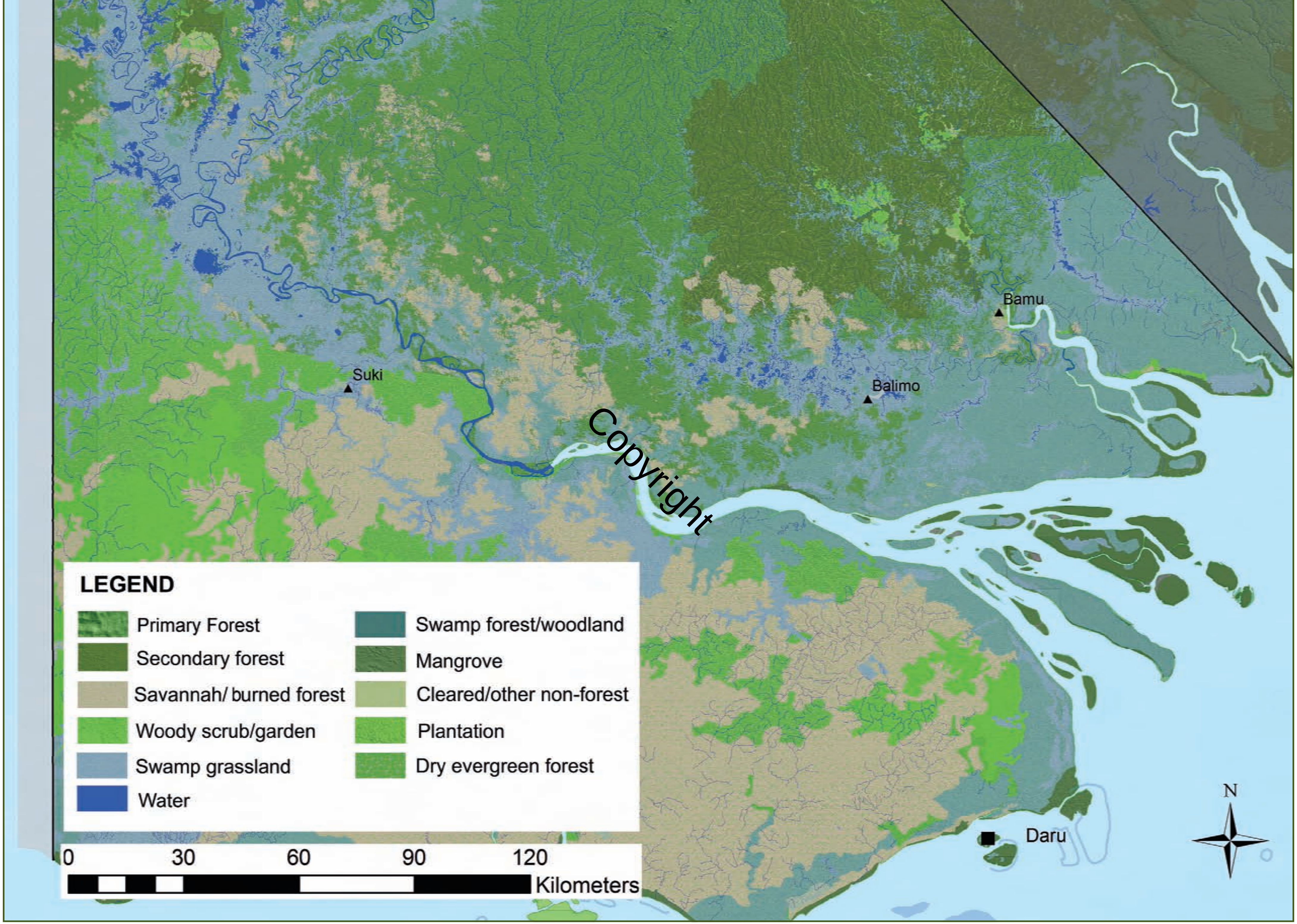
Provincial maps

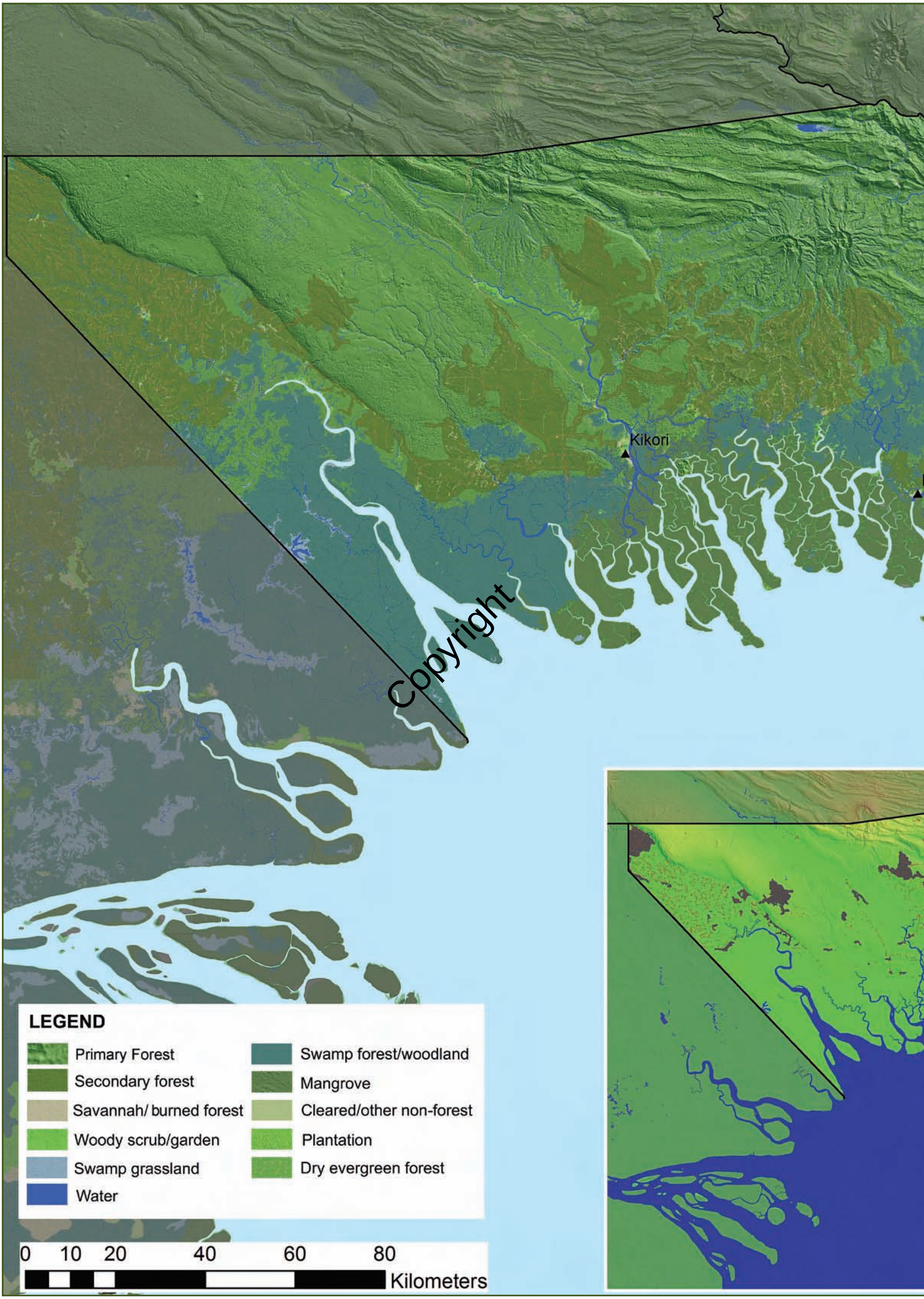
These maps show the 2014 vegetation map for each province in addition to the area logged between 2002 and 2014 as well as the area deforested between 2002 and 2014. They are presented in the following order:

- Western
- Gulf
- Central and Oro
- Milne Bay
- Southern Highlands and Hela
- Enga
- Jiwaka, Western Highlands, Chimbu, Eastern Highlands
- Morobe
- Madang
- East Sepik
- West Sepik (Sandaun)
- Manus
- New Ireland
- West New Britain
- East New Britain
- Bougainville

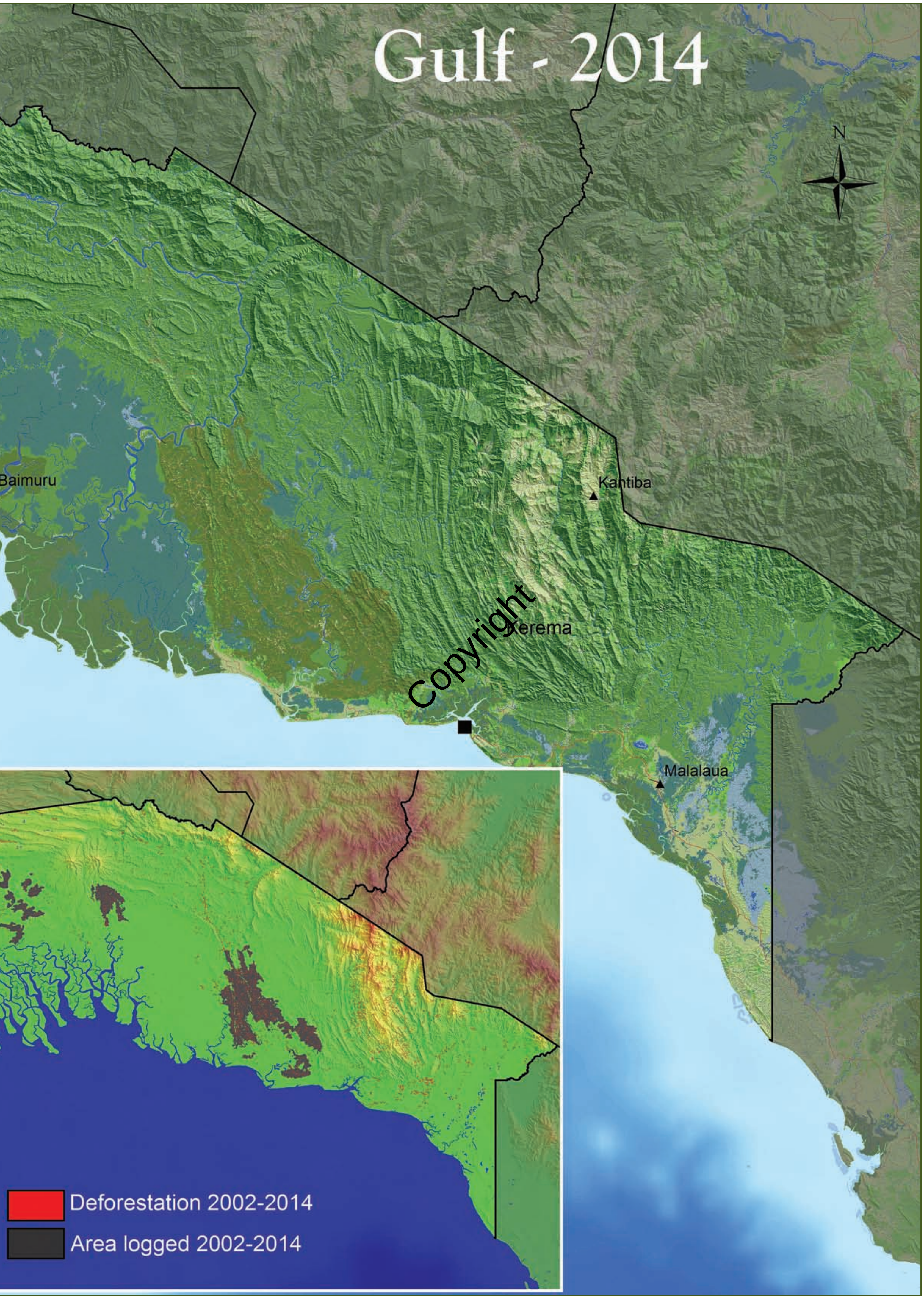
Western - 2014




Bamu
Suki
Balimo
Daru
N
LEGEND
Primary Forest
Secondary forest
Savannah/ burned forest
Woody scrub/garden
Swamp grassland
Water
Swamp forest/woodland
Mangrove
Cleared/other non-forest
Plantation
Dry evergreen forest
0
30
60
90
120
Kilometers

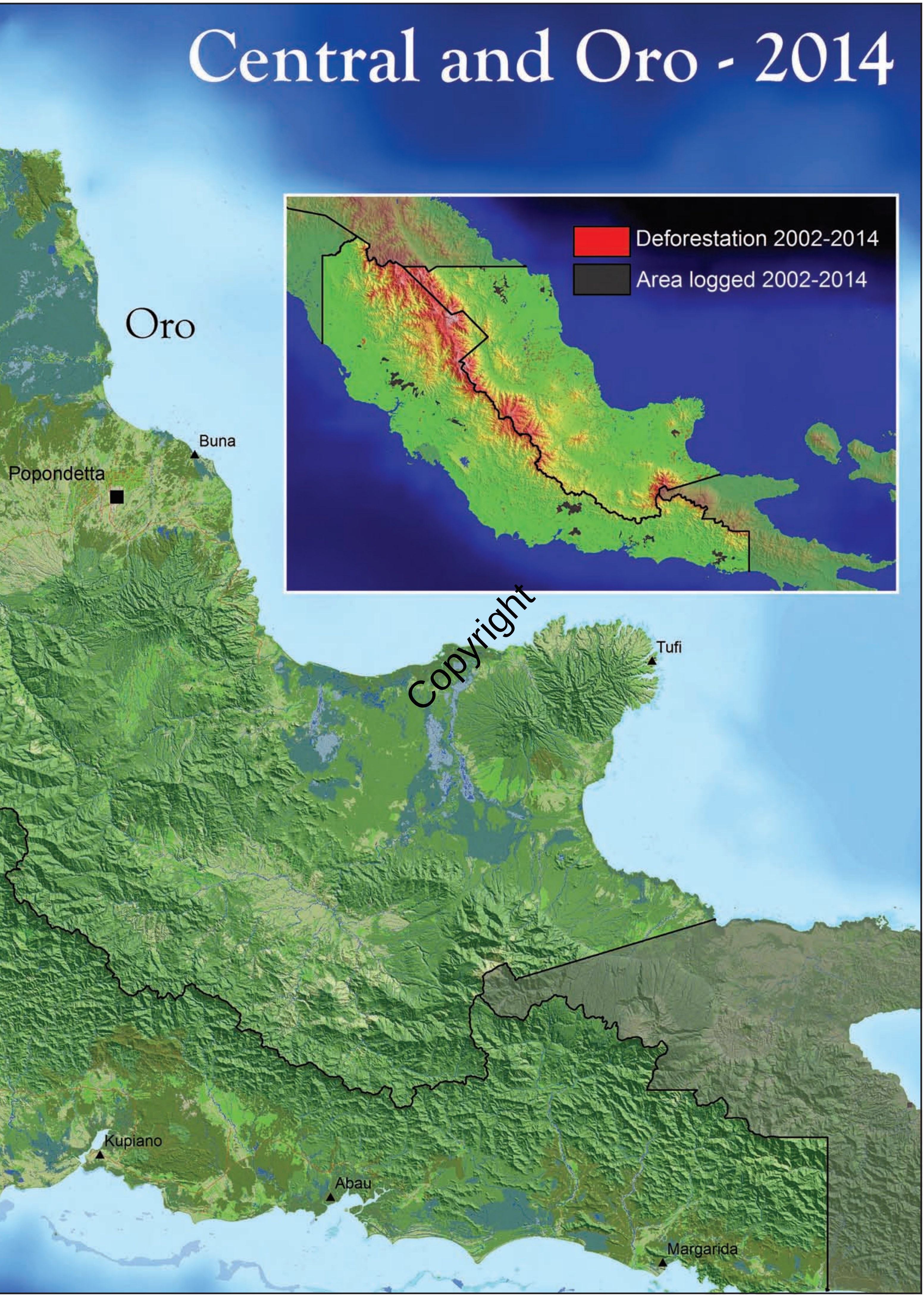

Kikori
LEGEND
Primary Forest
Secondary forest
Savannah/ burned forest
Woody scrub/garden
Swamp grassland
Water
Swamp forest/woodland
Mangrove
Cleared/other non-forest
Plantation
Dry evergreen forest
0
10
20
40
60
80
Kilometers

Gulf - 2014

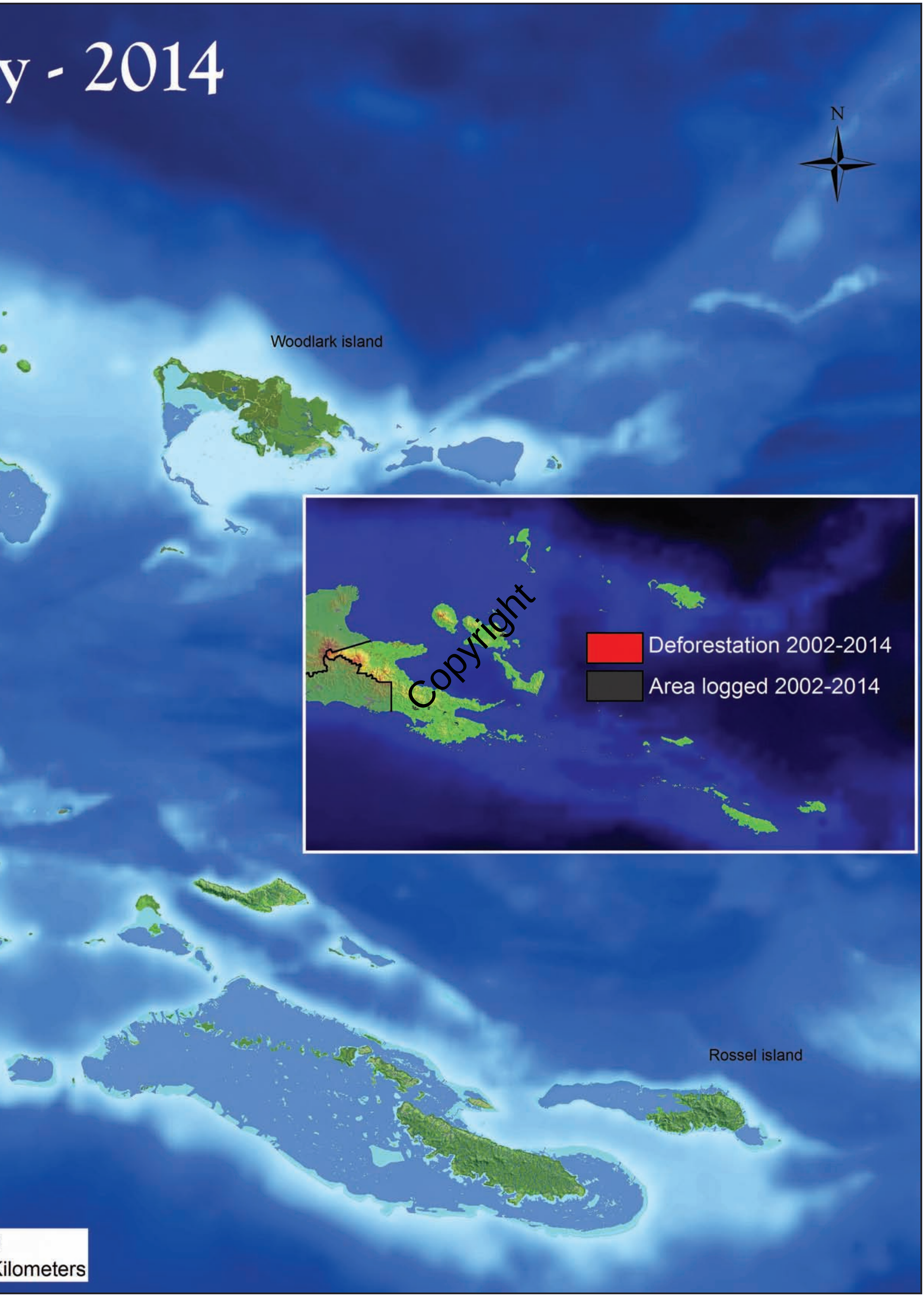

N
Baimuru
Kantiba
Kerema
Malalaua
🟥 Deforestation 2002-2014
⬛ Area logged 2002-2014

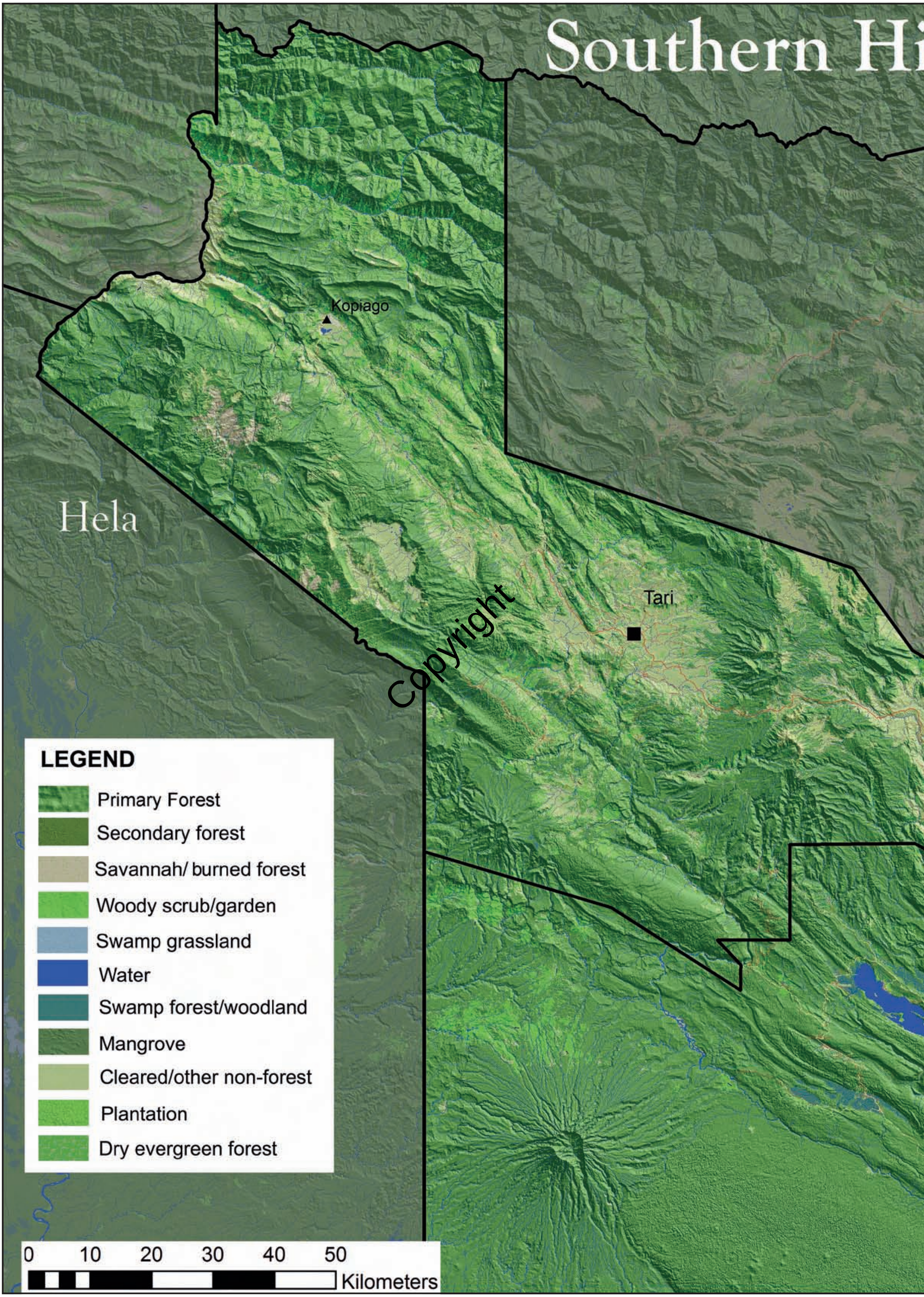

Tapini
Ioma
Woitape
Bereina
Kubuna
Yule Is.
Kokoda
Efogi
Central
Port Moresby
Sogeri
Kwikila
LEGEND
Primary Forest
Secondary forest
Savannah/ burned forest
Woody scrub/garden
Swamp grassland
Water
Swamp forest/woodland
Mangrove
Cleared/other non-forest
Plantation
Dry evergreen forest
N
0
10
20
40
60
80
Kilometers

Central and Oro - 2014




Milne Ba
Kiriwina island
Goodenough island
Fergusson island
Esa ala
Raba Raba
Normanby island
Alotau
LEGEND
Primary Forest
Secondary forest
Savannah/ burned forest
Woody scrub/garden
Swamp grassland
Water
Swamp forest/woodland
Mangrove
Cleared/other non-forest
Plantation
Dry evergreen forest
0
25
50
75
100
K


y - 2014
N
Woodlark island
Deforestation 2002-2014
Area logged 2002-2014
Rossel island
Kilometers


Southern Hi
Kopiago
Hela
Tari
Copyright
LEGEND
Primary Forest
Secondary forest
Savannah/ burned forest
Woody scrub/garden
Swamp grassland
Water
Swamp forest/woodland
Mangrove
Cleared/other non-forest
Plantation
Dry evergreen forest
0
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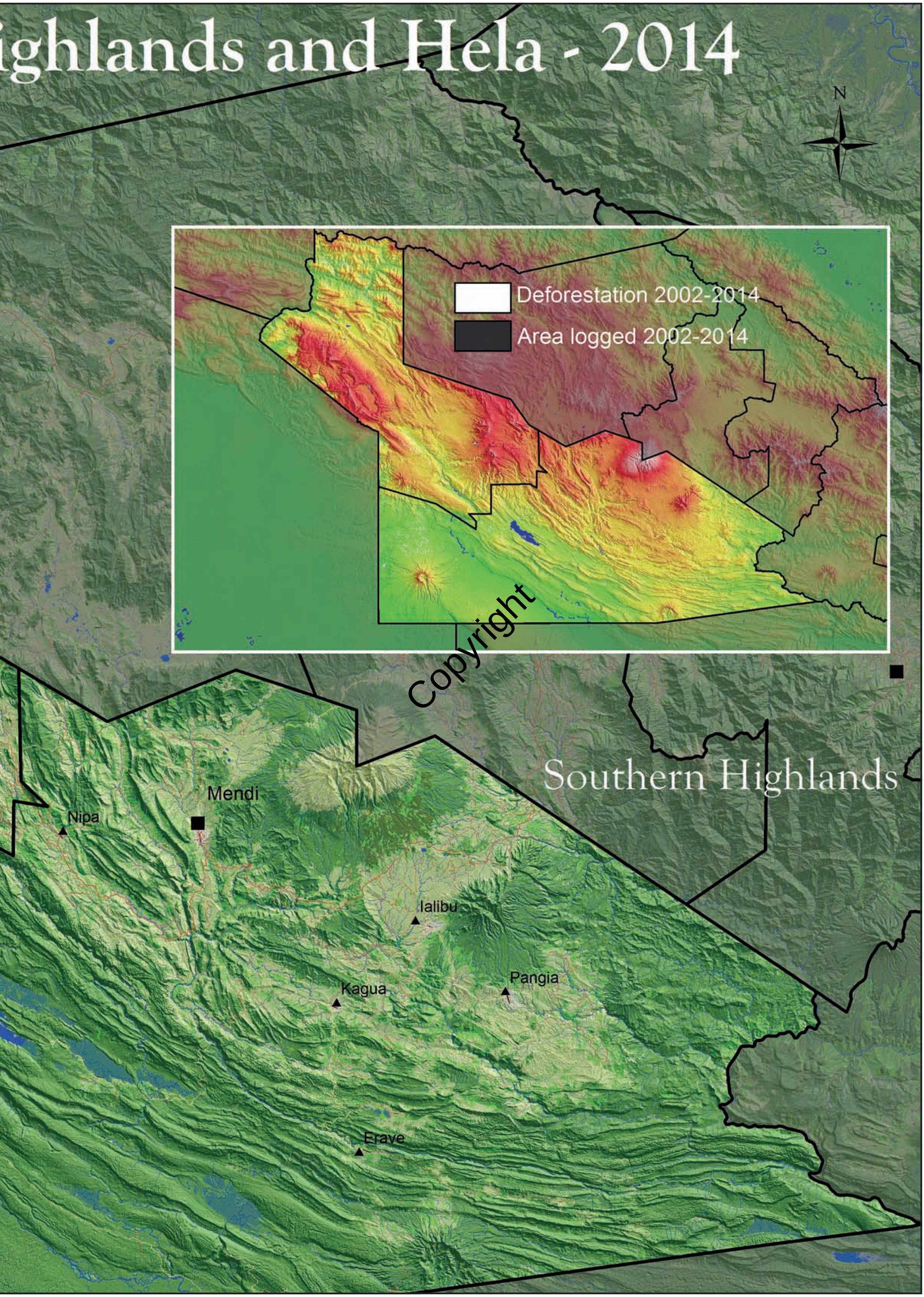
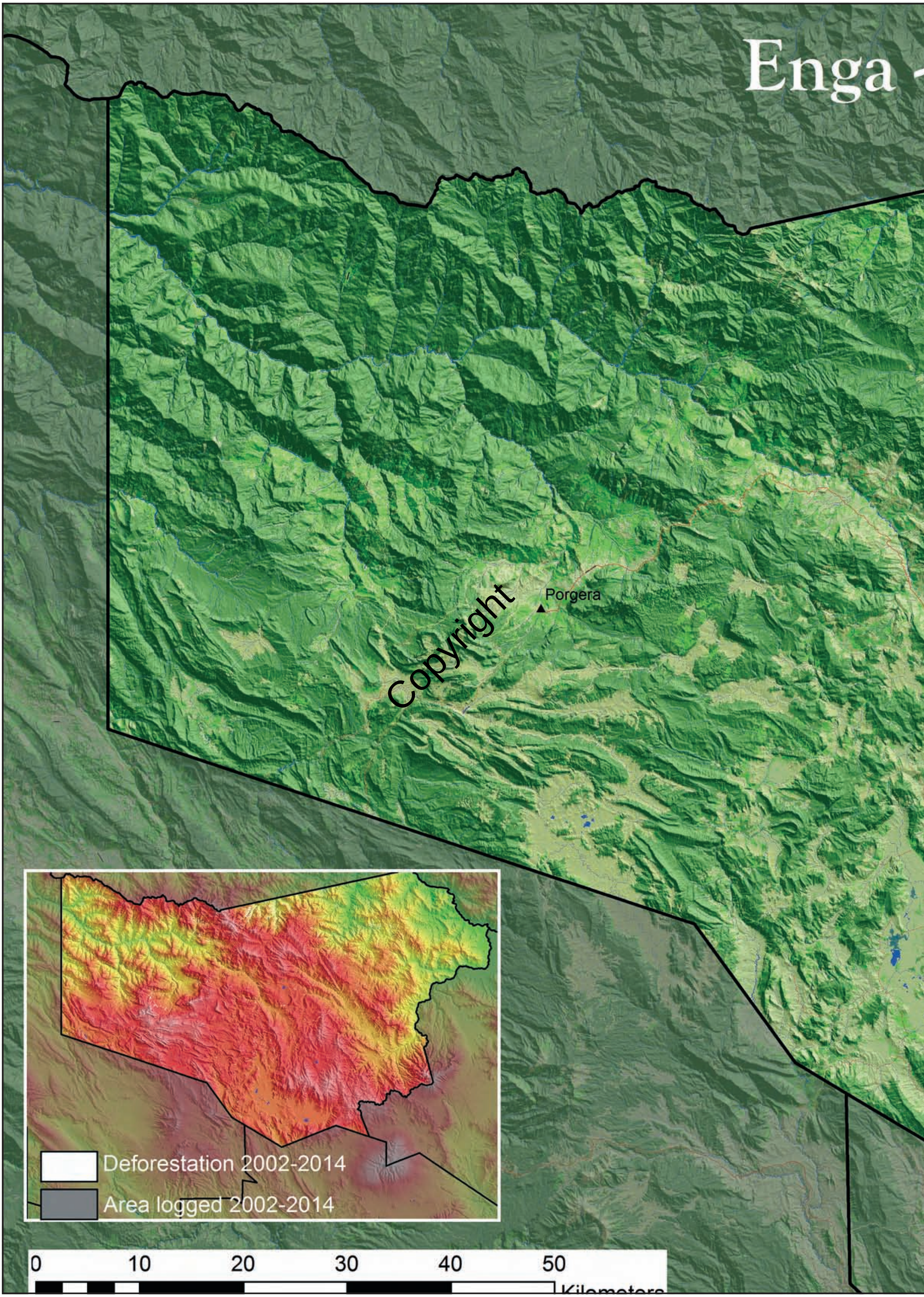
Kilometers


ighlands and Hela - 2014
N
Deforestation 2002-2014
Area logged 2002-2014
Southern Highlands
Mendi
Nipa
Ialibu
Pangia
Kagua
Erave


Enga
Porgera
Deforestation 2002-2014
Area logged 2002-2014
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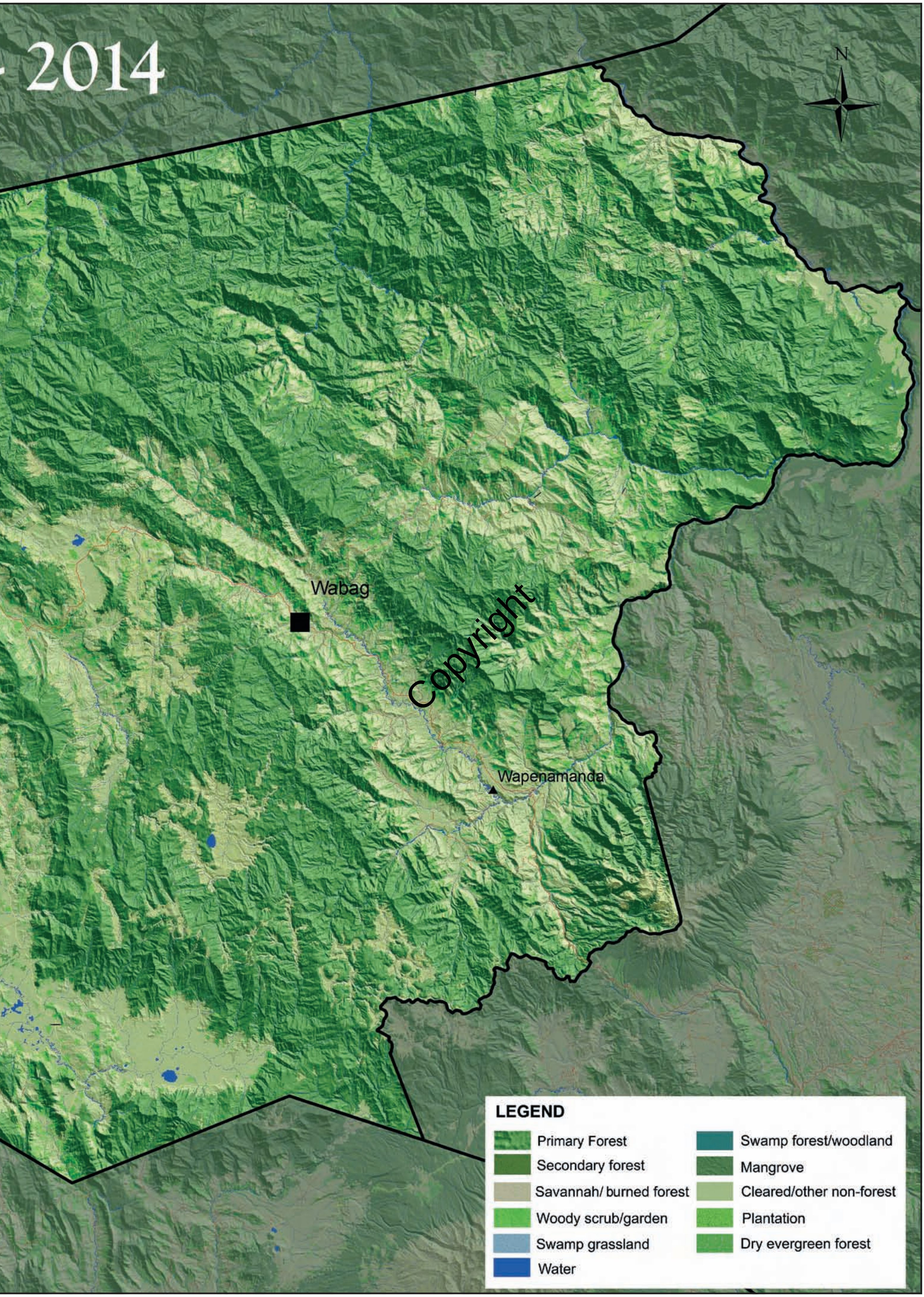
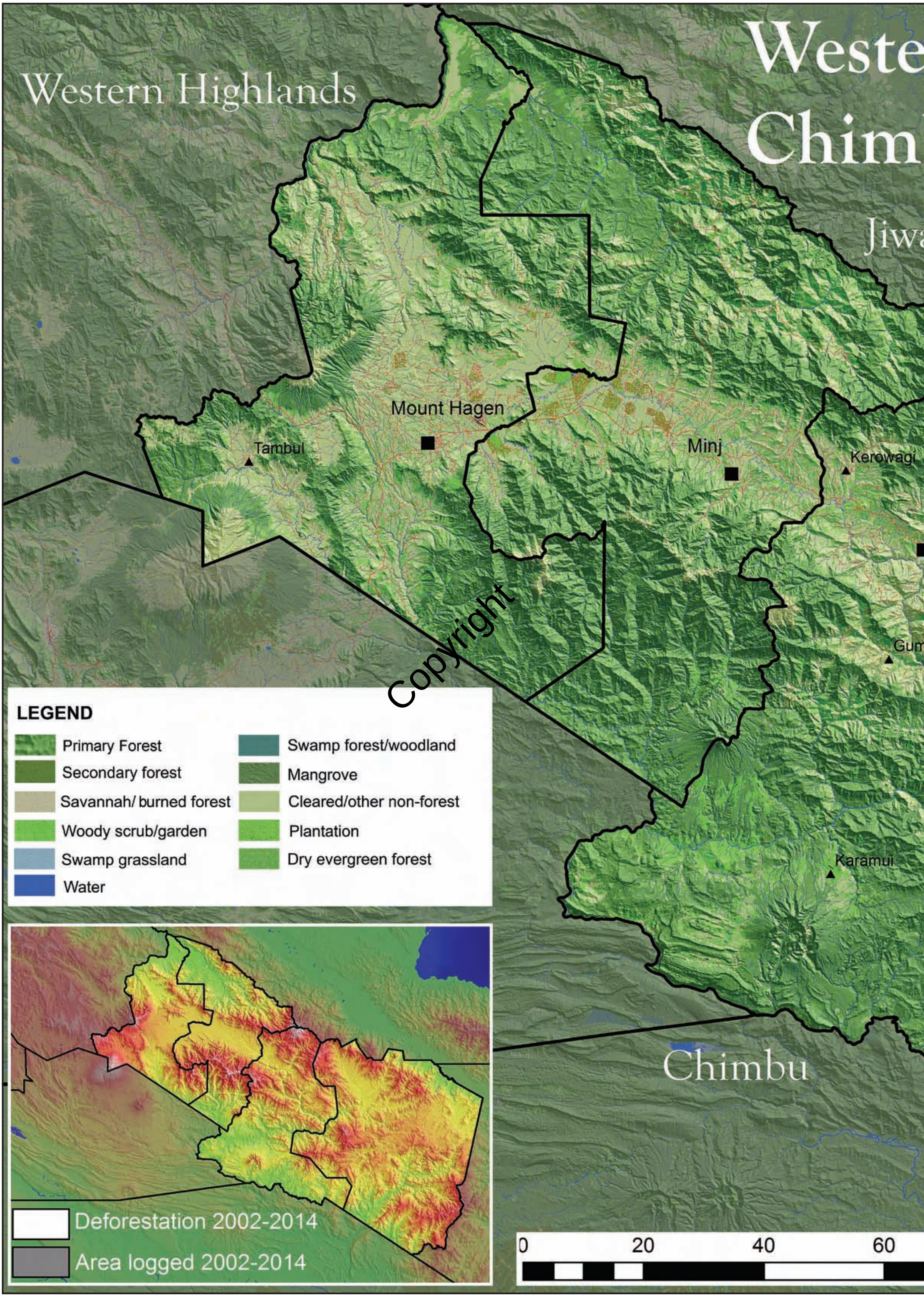
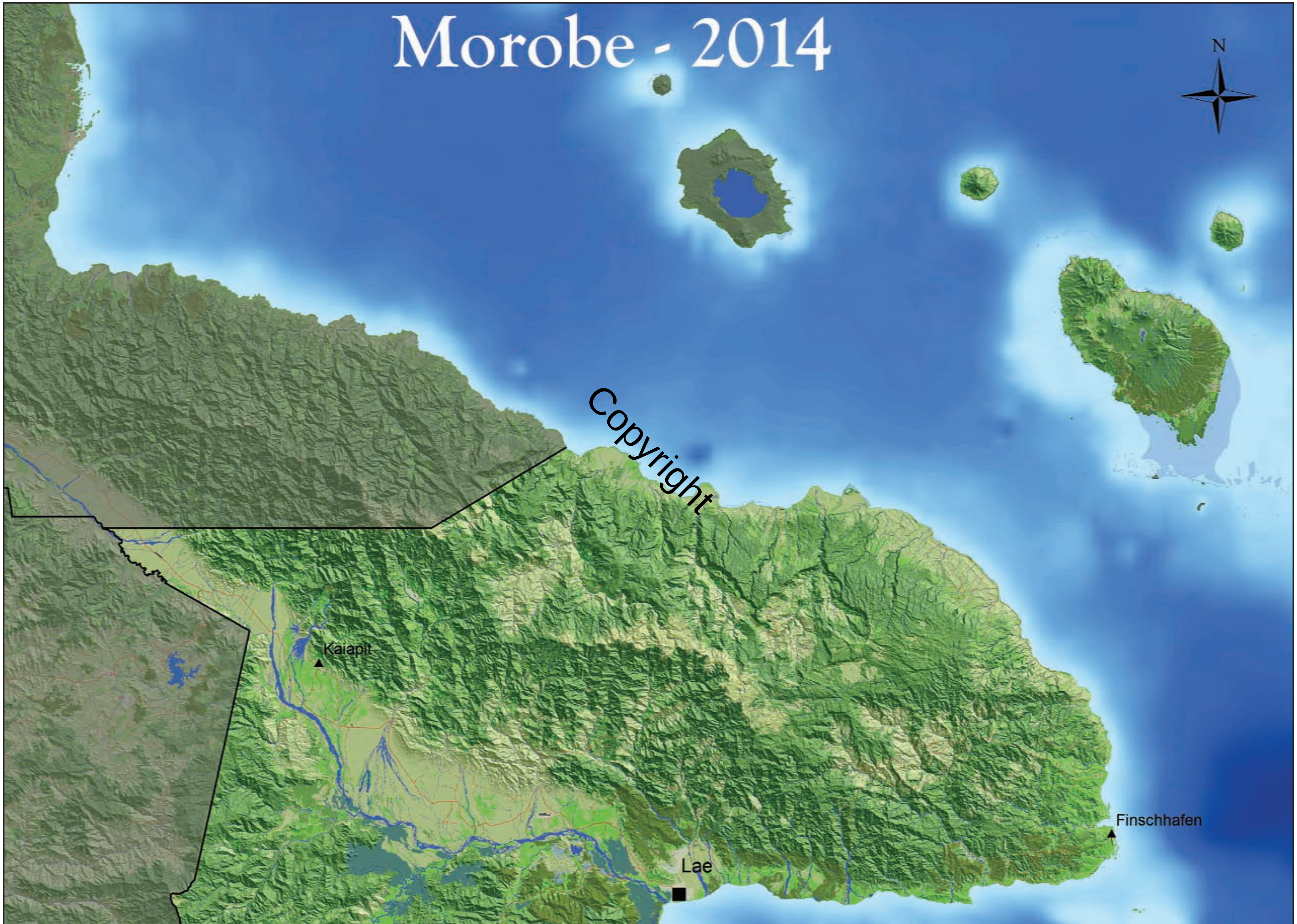
30
40
50

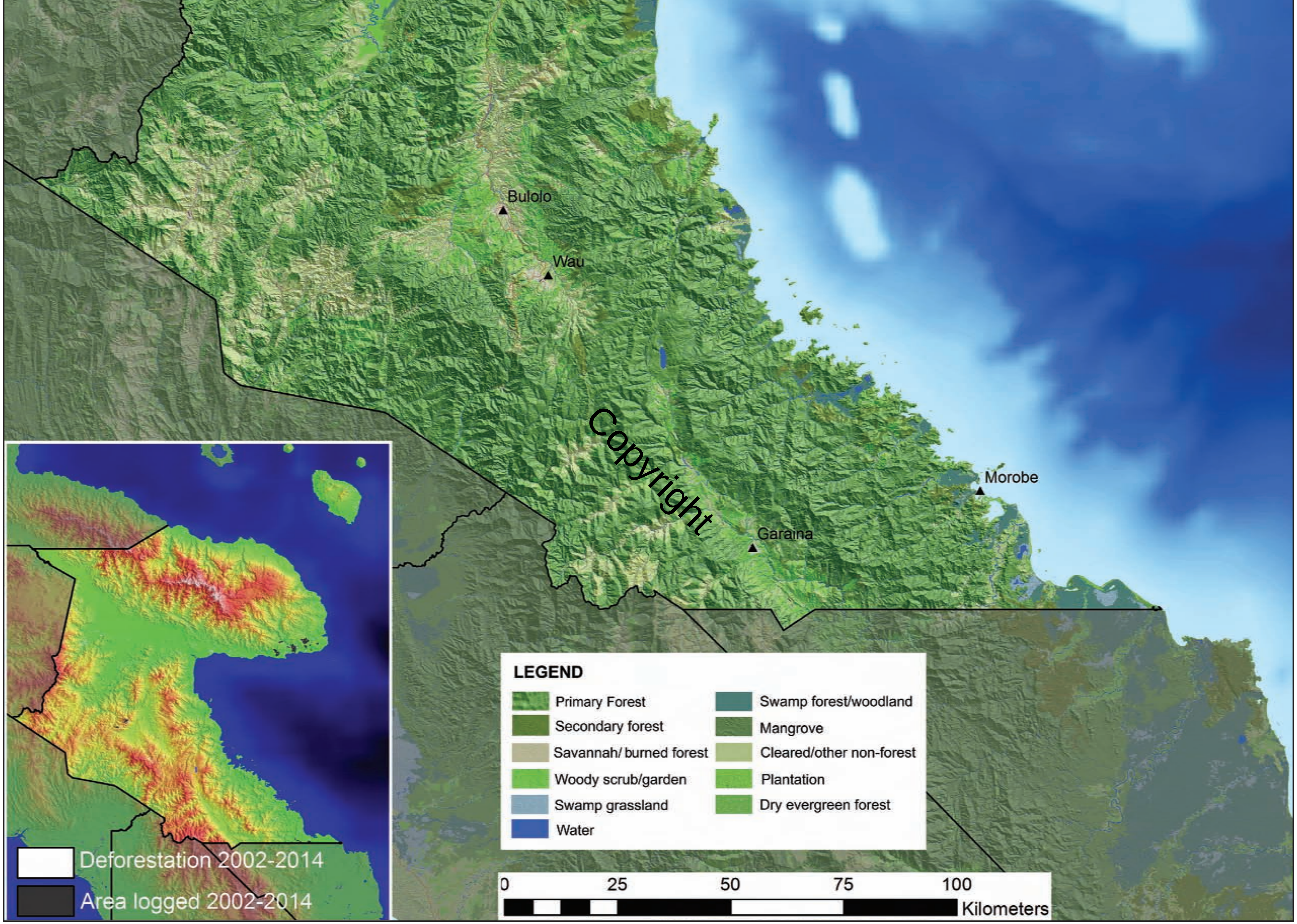

- 2014
N
Wabag
Wapenamanda
LEGEND
Primary Forest
Secondary forest
Savannah/ burned forest
Woody scrub/garden
Swamp grassland
Water
Swamp forest/woodland
Mangrove
Cleared/other non-forest
Plantation
Dry evergreen forest


Weste
Chim
Jiwa
Western Highlands
Mount Hagen
Tambul
Minj
Kerowagi
Gum
Karamui
Chimbu
LEGEND
Primary Forest
Secondary forest
Savannah/ burned forest
Woody scrub/garden
Swamp grassland
Water
Swamp forest/woodland
Mangrove
Cleared/other non-forest
Plantation
Dry evergreen forest
Deforestation 2002-2014
Area logged 2002-2014
0
20
40
60


ern Highlands, Jiwaka
bu, Eastern Highlands - 2014
aka
Mount Wilhelm
Eastern Highlands
Kundiawa
Goroka
Chuave
ine
Henganofi
Kainantu
Aiyura
Marawaka
80
Kilometers
N

Morobe - 2014




Bulolo
Wau
Morobe
Garaina
LEGEND
Primary Forest
Secondary forest
Savannah/ burned forest
Woody scrub/garden
Swamp grassland
Water
Swamp forest/woodland
Mangrove
Cleared/other non-forest
Plantation
Dry evergreen forest
0
25
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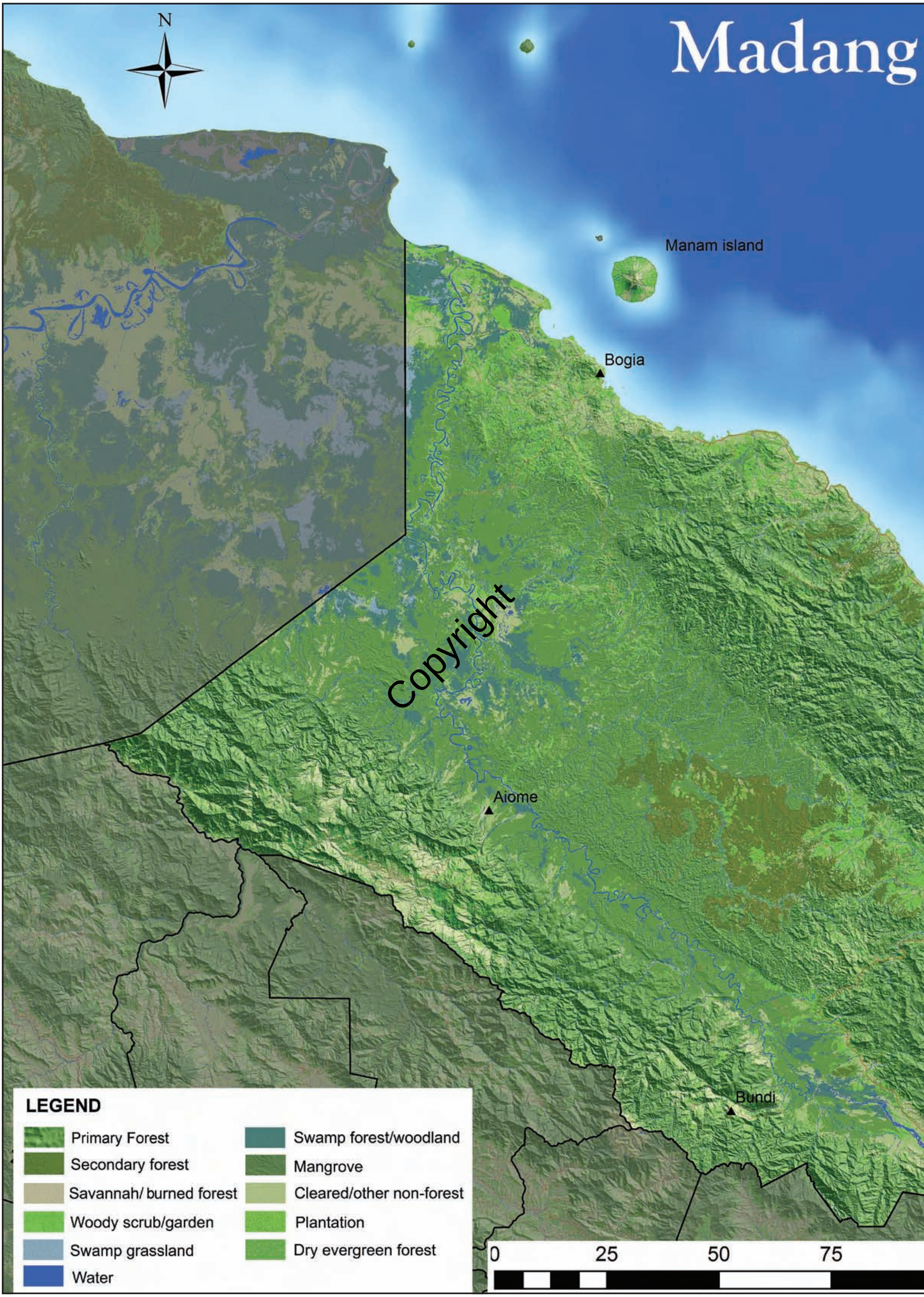
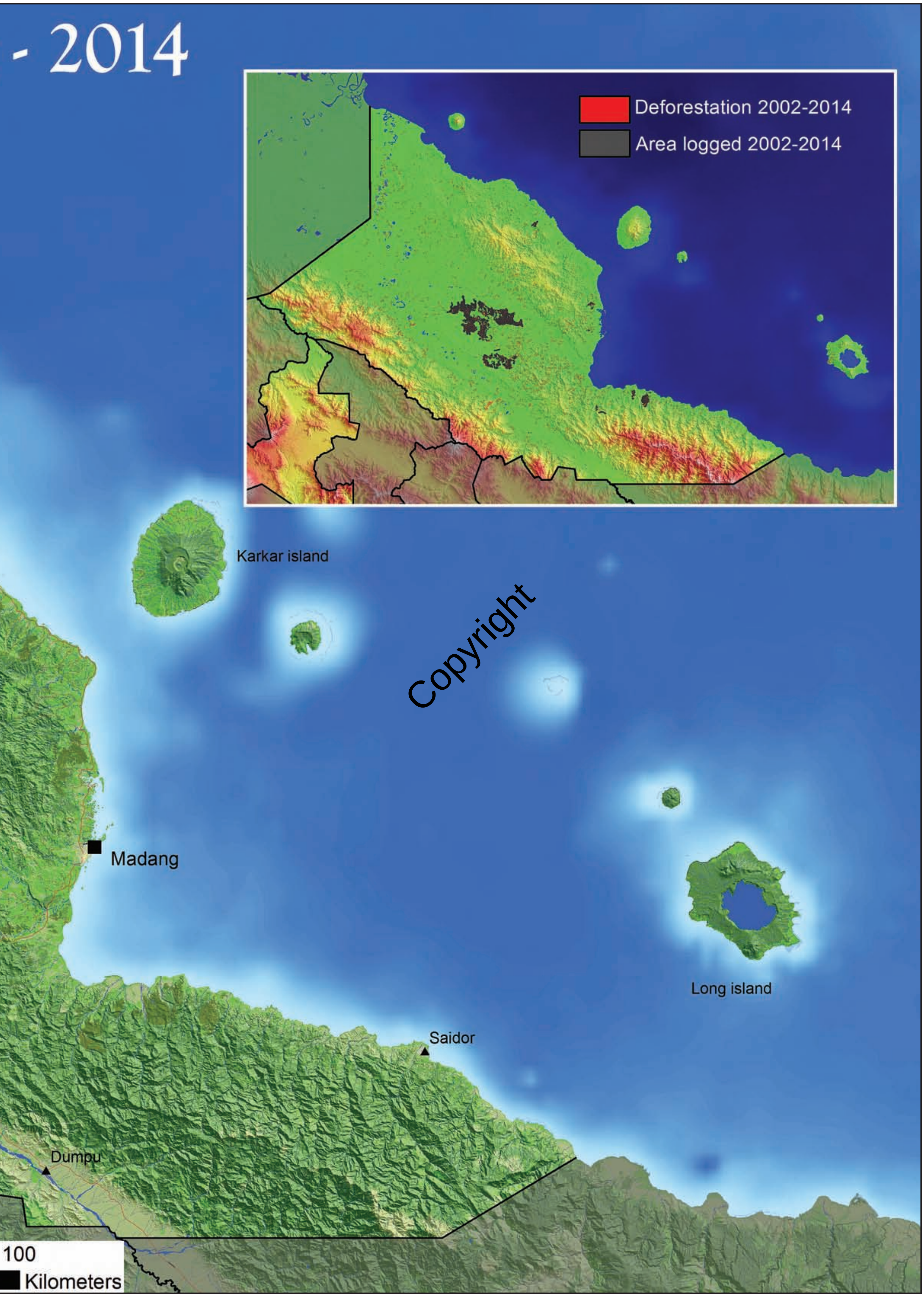
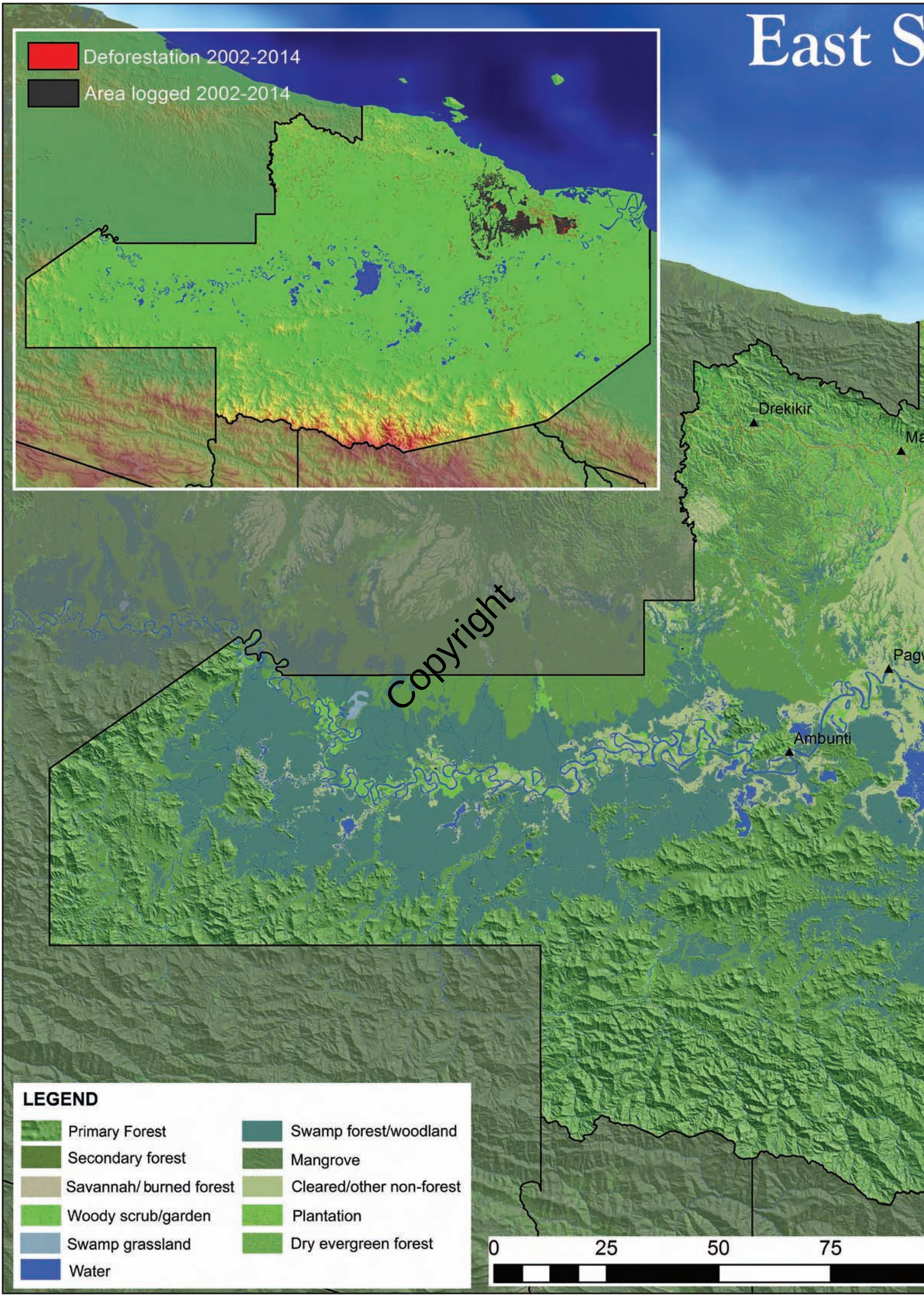
100
Kilometers
Deforestation 2002-2014
Area logged 2002-2014


Madang
N
Manam island
Bogia
Aiome
Bundi
LEGEND
Primary Forest
Secondary forest
Savannah/ burned forest
Woody scrub/garden
Swamp grassland
Water
Swamp forest/woodland
Mangrove
Cleared/other non-forest
Plantation
Dry evergreen forest
0
25
50
75

- 2014


🟥 Deforestation 2002-2014
▨ Area logged 2002-2014
Karkar island
Madang
Long island
Saidor
Dumpu
100
Kilometers


East S
Deforestation 2002-2014
Area logged 2002-2014
Drekikir
Ma
Pagw
Ambunti
LEGEND
Primary Forest
Secondary forest
Savannah/ burned forest
Woody scrub/garden
Swamp grassland
Water
Swamp forest/woodland
Mangrove
Cleared/other non-forest
Plantation
Dry evergreen forest
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75


epik - 2014
N
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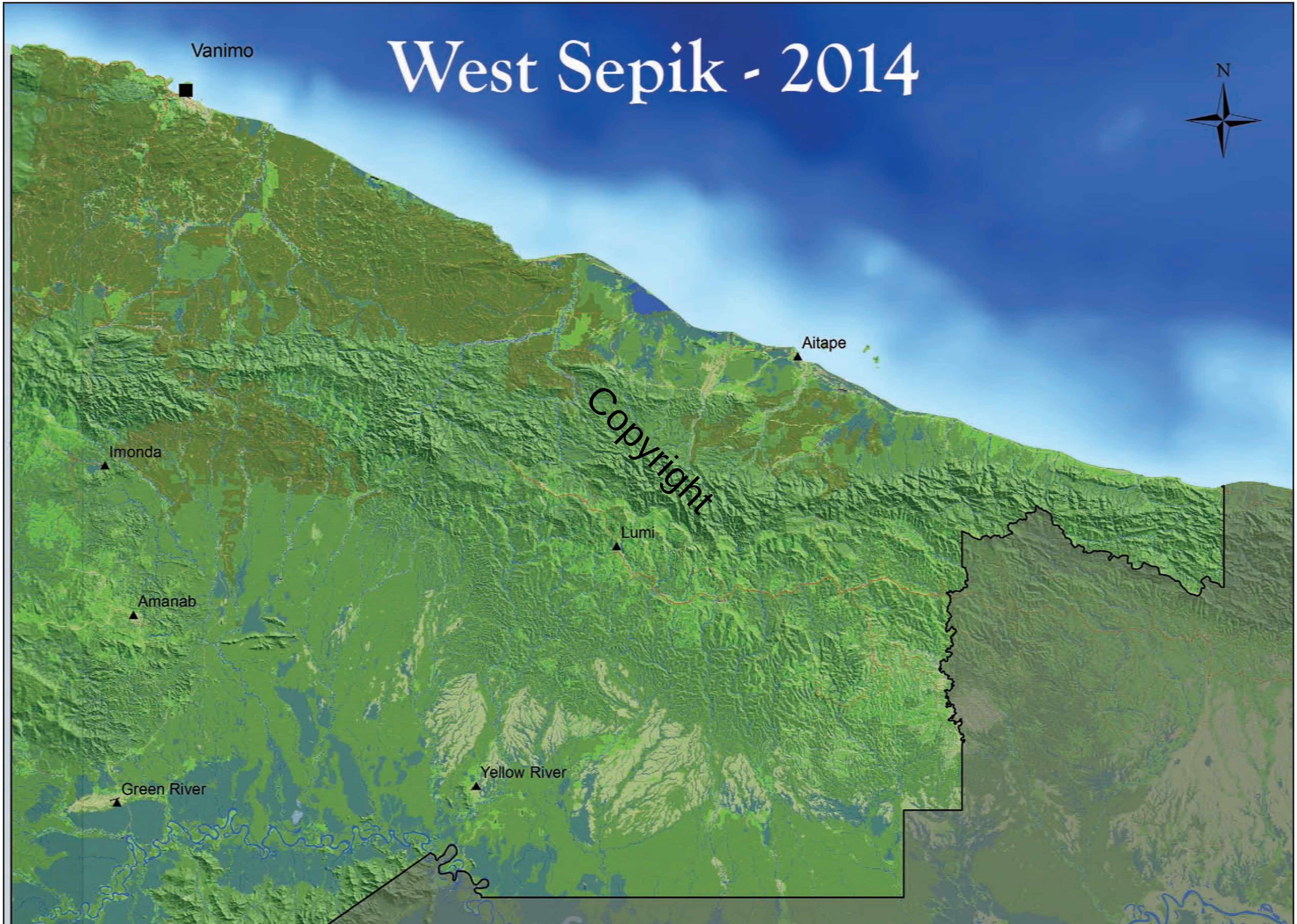
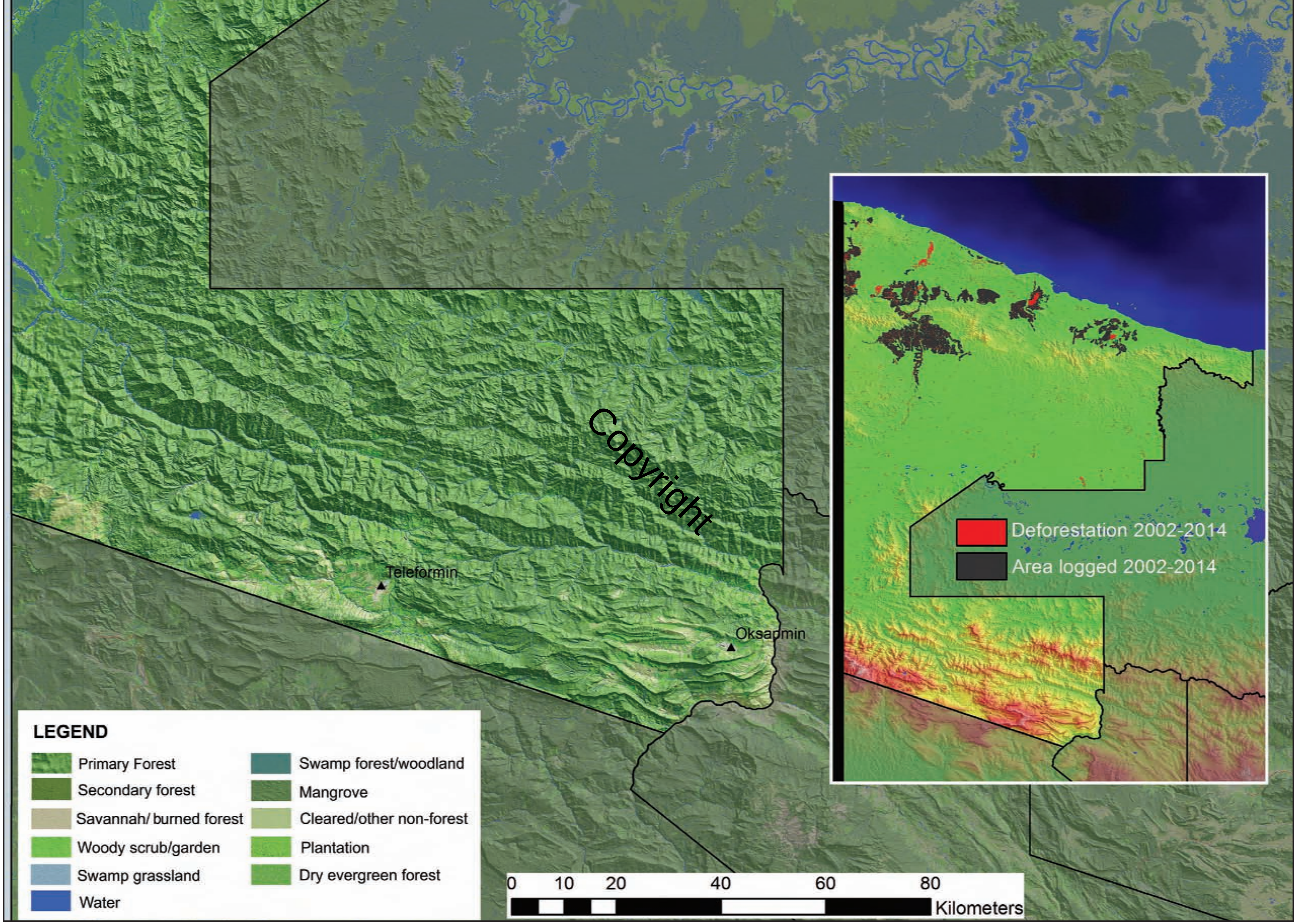
aprik
Yangoru
wi
Angoram
Amboin
100
Kilometers


West Sepik - 2014
N
Vanimo
Aitape
Imonda
Lumi
Amanab
Yellow River
Green River


Teleformin
Oksapmin
LEGEND
Primary Forest
Secondary forest
Savannah/ burned forest
Woody scrub/garden
Swamp grassland
Water
Swamp forest/woodland
Mangrove
Cleared/other non-forest
Plantation
Dry evergreen forest
0
10
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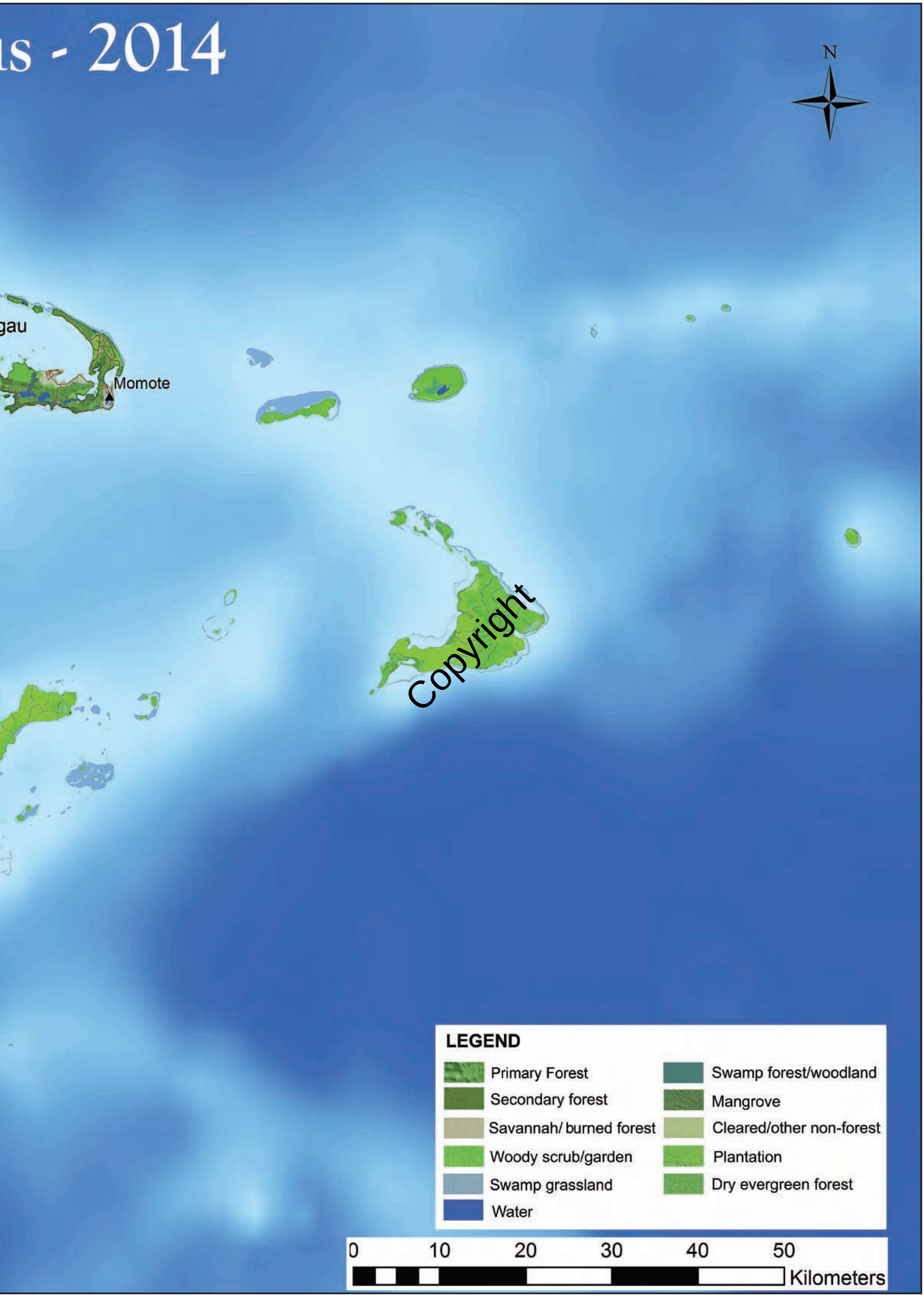
80
Kilometers
Deforestation 2002-2014
Area logged 2002-2014


Manu
Lessau
Loreng
Deforestation 2002-2014
Area logged 2002-2014


s - 2014
N
gau
Momote
LEGEND
Primary Forest
Secondary forest
Savannah/ burned forest
Woody scrub/garden
Swamp grassland
Water
Swamp forest/woodland
Mangrove
Cleared/other non-forest
Plantation
Dry evergreen forest
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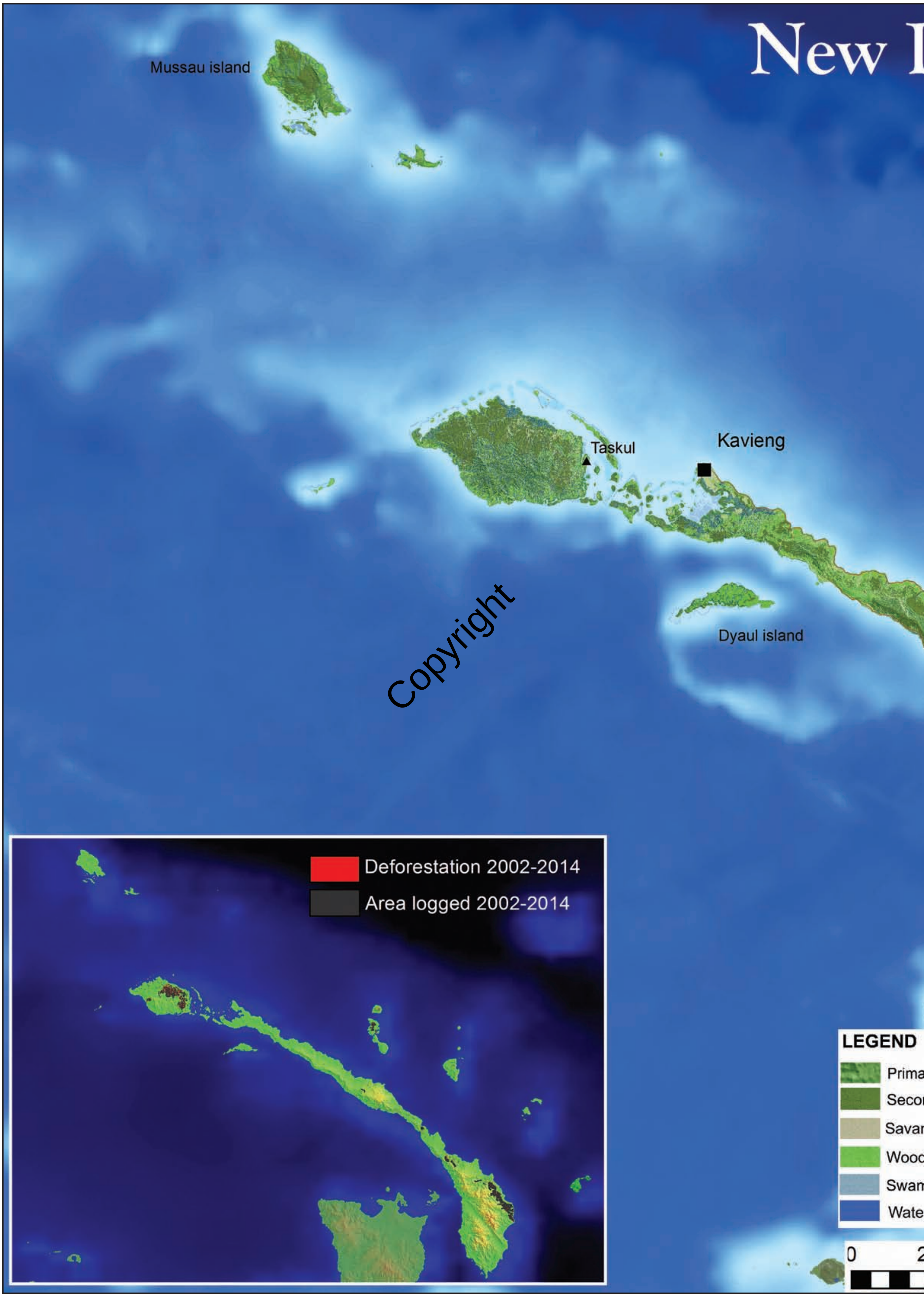
Kilometers


New I
Mussau island
Taskul
Kavieng
Dyaul island
Deforestation 2002-2014
Area logged 2002-2014
LEGEND
Prima
Secor
Savar
Wooc
Swan
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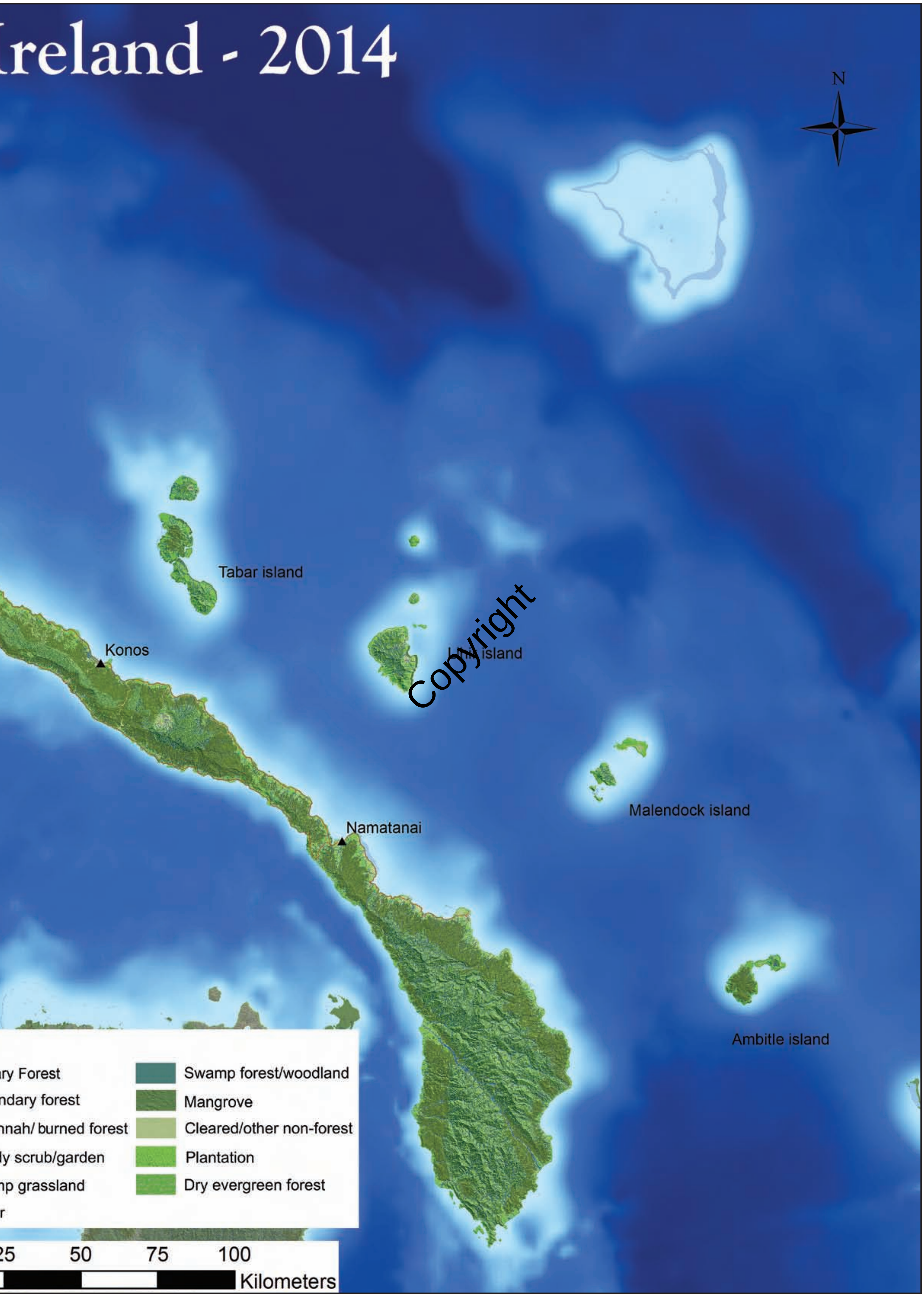
2


Ireland - 2014
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Tabar island
Konos
island
Malendock island
Namatanai
Ambitle island
ry Forest
ndary forest
nnah/ burned forest
ly scrub/garden
np grassland
r
Swamp forest/woodland
Mangrove
Cleared/other non-forest
Plantation
Dry evergreen forest
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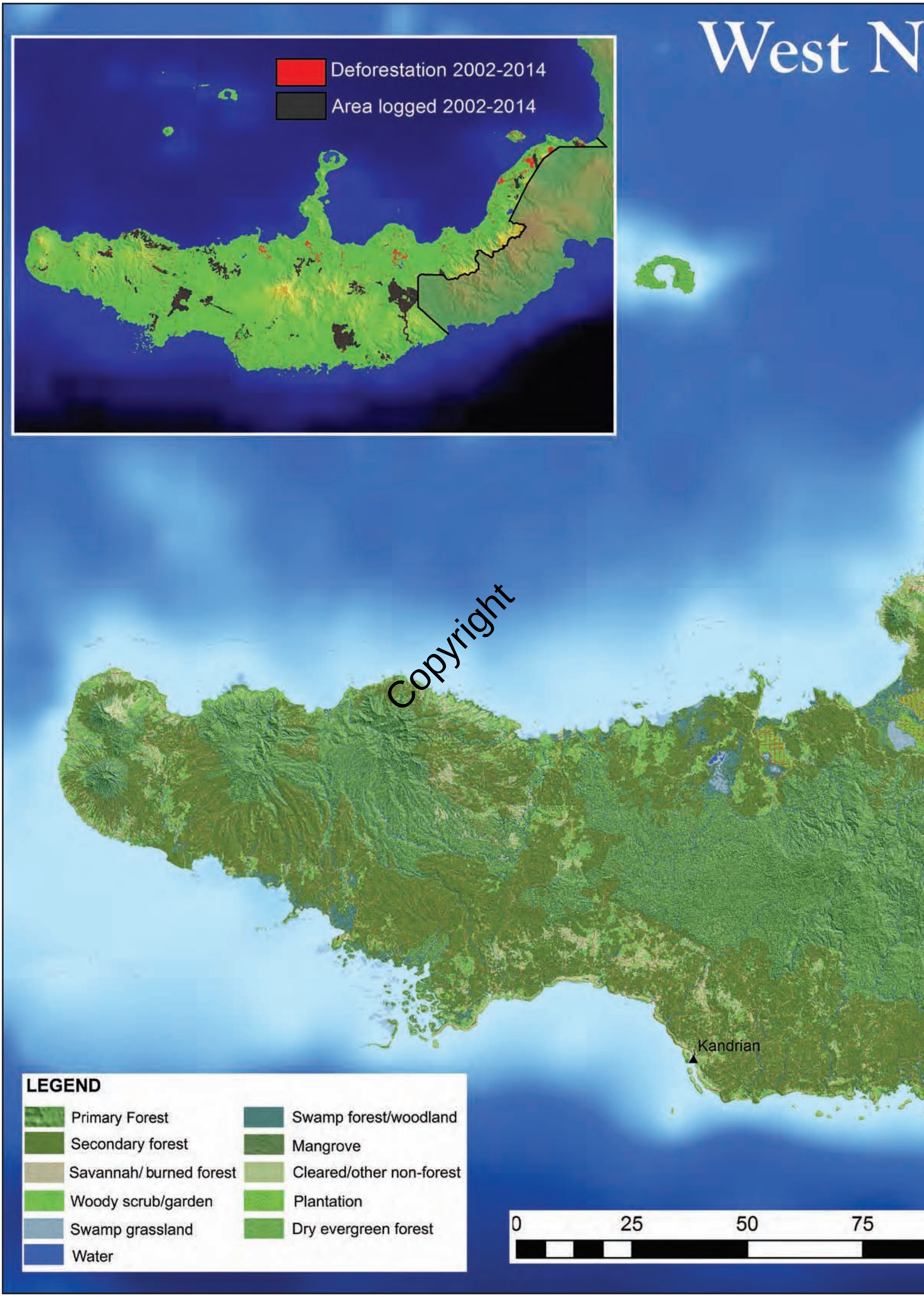
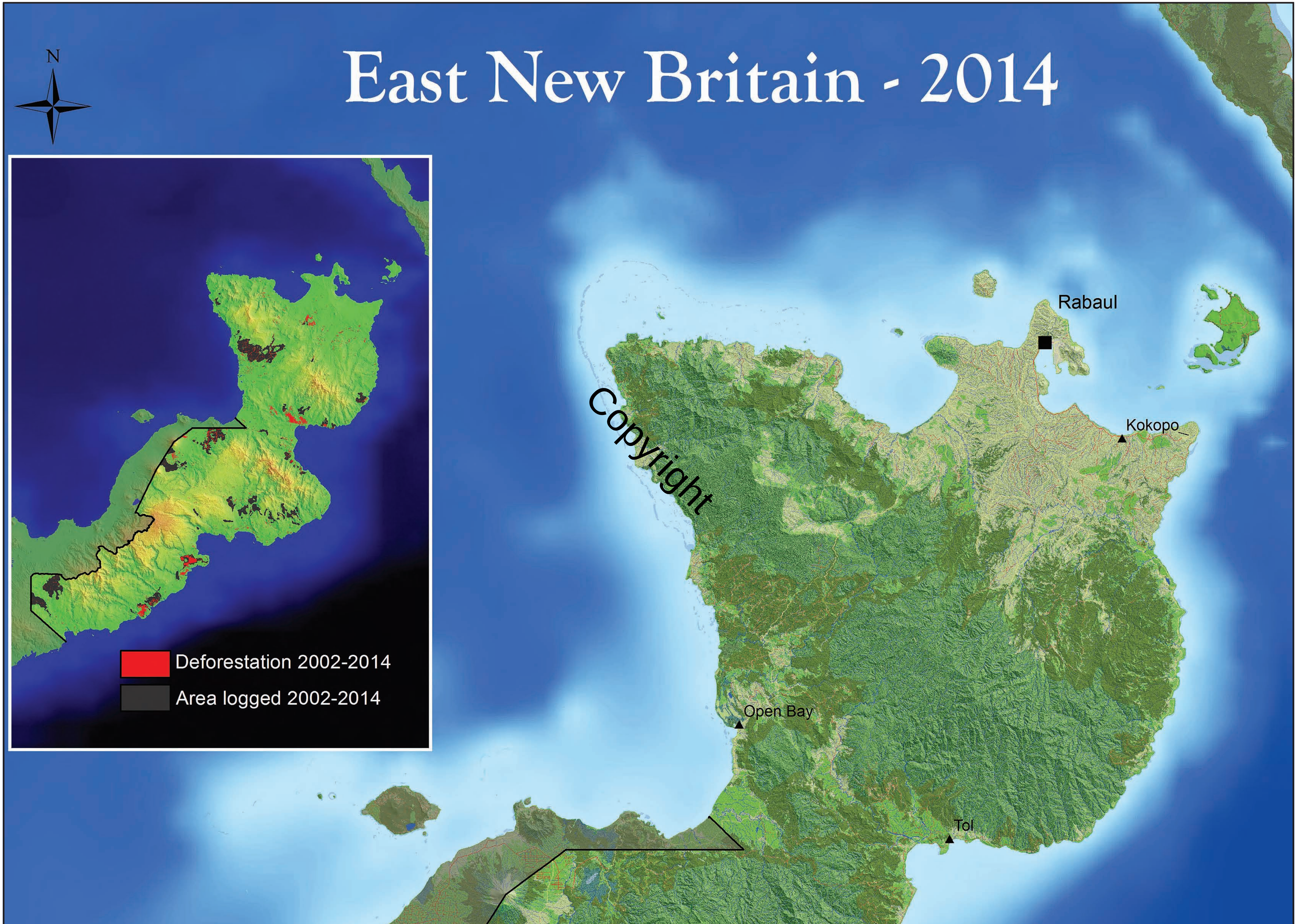
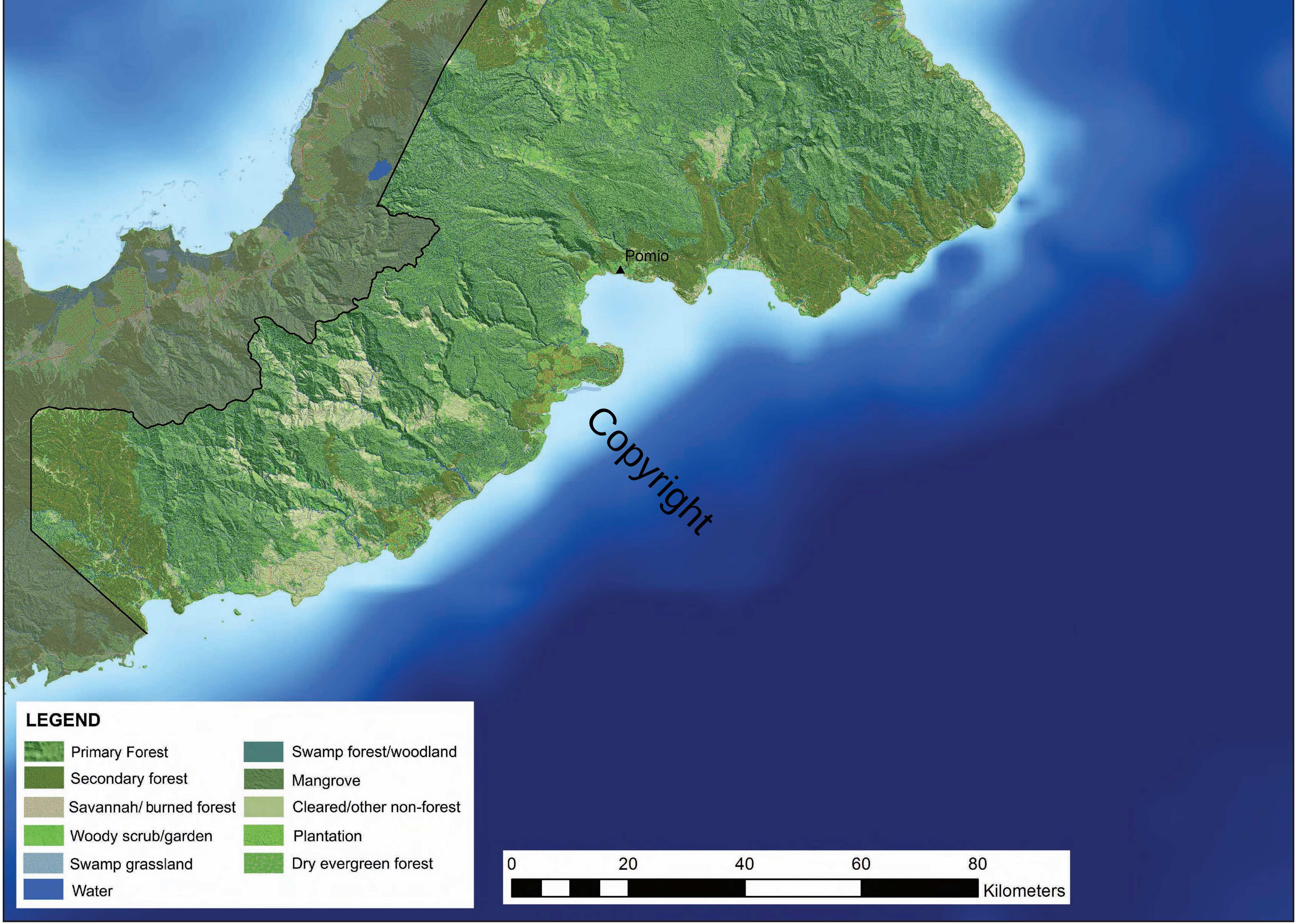
100
Kilometers


West N
Deforestation 2002-2014
Area logged 2002-2014
Kandrian
LEGEND
Primary Forest
Secondary forest
Savannah/ burned forest
Woody scrub/garden
Swamp grassland
Water
Swamp forest/woodland
Mangrove
Cleared/other non-forest
Plantation
Dry evergreen forest
0
25
50
75


ew Britain - 2014

East New Britain - 2014




Pomio
LEGEND
Primary Forest
Secondary forest
Savannah/ burned forest
Woody scrub/garden
Swamp grassland
Water
Swamp forest/woodland
Mangrove
Cleared/other non-forest
Plantation
Dry evergreen forest
0
20
40
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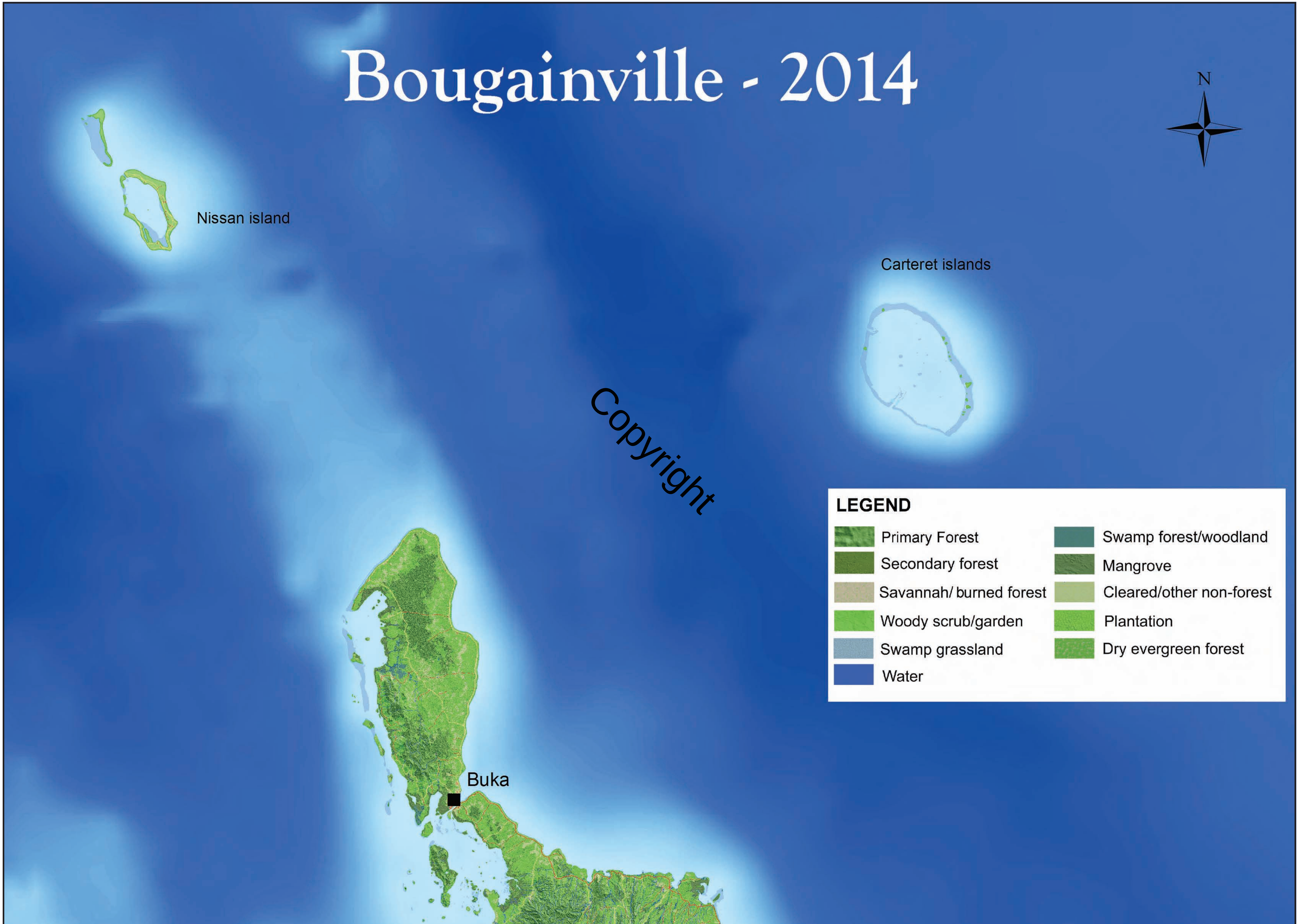
80
Kilometers


Bougainville - 2014
N
Nissan island
Carteret islands
Buka
LEGEND
Primary Forest
Secondary forest
Savannah/ burned forest
Woody scrub/garden
Swamp grassland
Water
Swamp forest/woodland
Mangrove
Cleared/other non-forest
Plantation
Dry evergreen forest


Deforestation 2002-2014
Area logged 2002-2014
Wakunai
Kieta
Boku
Buin
0
20
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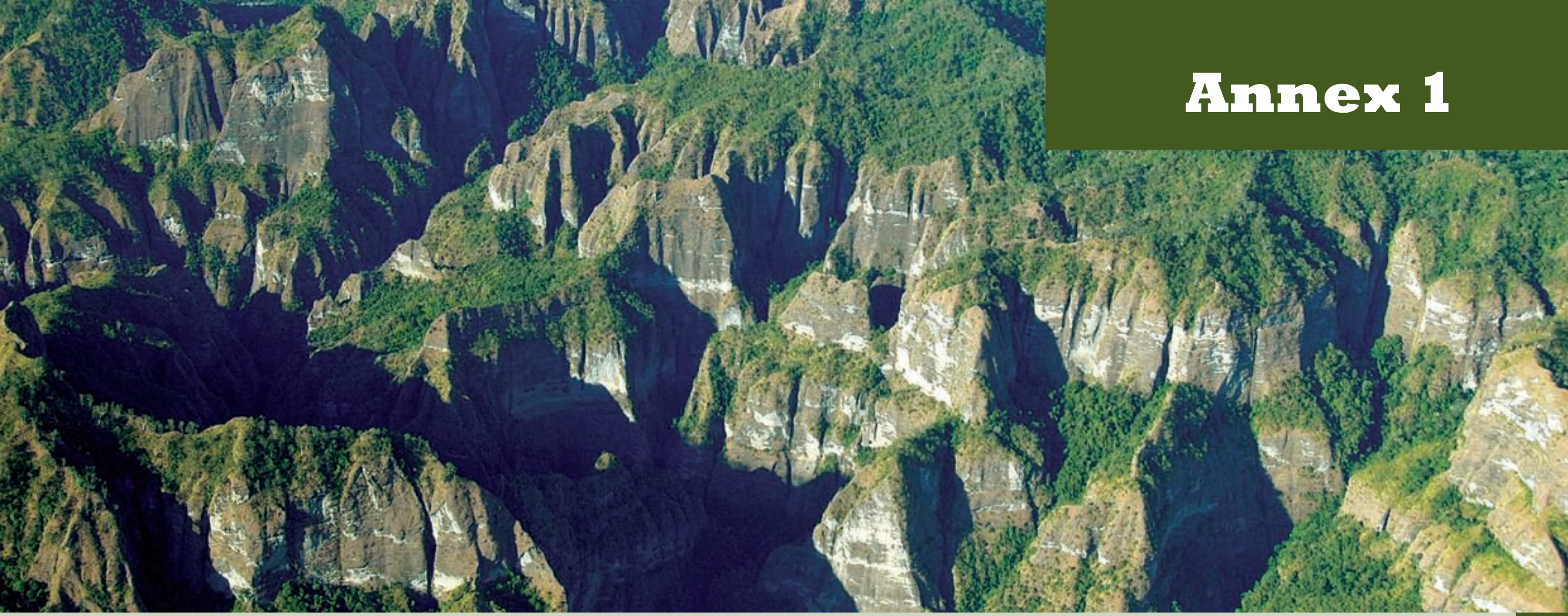
Kilometers



Annex 1

Methods

To document the changes in PNG's forests for the 2015 State of the Forests Report, we compared the 2002 forest map created in the 1972 -2002 *State of the Forests report*, and a newly created 2014 forest map. As in the previous State of the Forests report, "forest" is defined as closed canopy rainforest, and we have measured the area of rainforest loss which we refer to as "deforestation".

Area calculations

All imagery used to produce the 2014 vegetation map was orthorectified against the 2002 vegetation map using 20-30 ground control points for each image with a root mean square error of +/- 20-30 m. This was done in order to accurately detect change in forest boundaries since 2002. Areas were calculated in the UTM projection using the Mapinfo GIS. As different analyses calculate area in different ways, minor differences in total area between the State of the Forests report and other works are likely due to differences in the map projection used, or differences in orthorectification outcomes.

Creation of the 2014 forest map

A new 2014 forest layer was created using Landsat 8, 30 m resolution satellite imagery (courtesy of U.S Geological Survey). Forest cover across the whole nation could not be mapped using a single year of imagery, due to almost perpetual cloud cover in some areas. For this reason, we used images recorded between 2013 and 2015 to map the entire extent of PNG, which we refer to as the "2014" data.

The Carnegie Landsat Analysis System (CLASlite) was used as the first step in producing maps of forest and deforestation. CLASlite uses a digital library of the spectral signature of different land cover types derived from extensive field surveys (Asner *et al.*, 2009). The program uses an automated algorirthm to "unmix" image pixels into the fraction of photosynthetic (live) vegetation cover (PV), non-photosynthetic vegetation (dead) cover (NPV), and bare substrate (BS)(Asner *et al.*, 2009). A threshold of 80% photosynthetic vegetation and 15-20% bare substrate have been used in other nations to distinguish "forest" from "non-forest" (Bryan *et al.*, 2013). In the results it was found that in some places garden areas and oil palm plantations were being included as "forest". Therefore the initial CLASlite map of land cover with greater than 80% PV and less 15% bare substrate is referred to as a map of '2014 tree/palm cover' in which there are two classes – 'tree/palm cover' (>80% PV and <15% BS) and non-forest (all other values). This map was then converted into a vector format, and overlaid it onto the original Landsat 8 images in a Geographic Information System (GIS). Any areas of garden, plantation or oil palm areas that had been mis-labelled as forest were then reclassified to produce a map of "forest" and "non-forest" for 2014.

This forest/non-forest map was then manually checked and classes were adjusted to match the same classification system used in the 2002 vegetation layer. After the classification was completed, the 2002 forest map was compared with the 2014 map to identify areas of change. In addition to CLASlite and the UPNG RSC 2002 vegetation map, parts of the Hansen *et al.*, (2013) map of deforestation was used to fill in some cloud gaps. The Hansen *et al.*, (2013) map of the area deforested 2000-2012 overlapped substantially the time period of our analysis. However, several adjustments were made to the Hansen dataset in order to make it compatible with the PNG vegetation classification. Some areas identified as deforestation in the Hansen dataset were in fact existing oil palm or timber plantations that had been harvested. In the State of the Forests report, oil palm was not classified as forest, so these areas were removed from the measurement of deforestation. In addition the Hansen dataset identified areas of garden or woody scrub that had been cleared as "deforestation". In this study assessment, these garden areas are not classified as forest, hence were removed from the assessment of deforestation. Deforestation was defined to be consistent with the 1972-2002 change assessment, as the conversion of closed canopy rainforest to non-forest (woody scrub/garden, cleared land, plantation, grassland/savannah). We do not include the conversion of woody scrub to other non-forest classes, nor do we include the conversion of woody swamp to non-forest classes.

Mapping of logged area between 2002 & 2014

The map of logged area 1972-2002 was the same used in the previous State of the Forests report (Shearman *et al.*, 2008), and the same method was used to map forests that were logged between 2002 and 2014. This involved mapping recent logging-related deforestation and degradation using the visual interpretation of logging roads, skid tracks and canopy gaps to delineate a timber extraction radius for all commercial logging activity. Forests apparent in the 2014 vegetation map within our timber extraction radius were designated as 'degraded' and clearances were designated as 'deforested' due to logging. Areas within logging concessions outside of this radius were assumed not to have been logged.

While the first and second order roads from logging operations are visible in Landsat imagery for a decade or longer post-logging, the associated canopy gaps and skid trails are usually covered over by regrowth within 1 to 5 years (Nepstad *et al*, 1999) making them difficult to discern from unlogged forest. Older logging is therefore difficult to detect from Landsat imagery (Asner *et al.*, 2005).

For these reasons we used logging roads identified during image classification and where visible skid trails, to delineate areas of older logging (>5 years) activity. The use of mapped logging roads as surrogates for assessing the extent of logging has been widely used to overcome problems with automatic classification caused by the relatively minor differences between the spectral properties of logged and unlogged forests (Bryan *et al.*, 2013, Miettinen *et al.*, 2014). Logging roads were manually digitised from consecutive Landsat 8 images recorded between 2013 and 2015. In places with perpetual cloud cover, Landsat 7 images recorded between 2002 and 2013 were also use to digitise logging roads from across the whole country. The result was a map of all logging roads present over the period 2013-2015. These logging roads formed the basis of the timber extraction radius.

The result was a map of logged forests in 2014, with forests logged in the period 1972-2002 mapped separately from forests logged between 2002 and 2014.

Validation and of the 2014 forest map

In order to validate the 2014 forest map, very high resolution (1-10 m) digital globe imagery was obtained for a selection of locations, across a range of vegetation types in every province. Forest boundaries in the 2014 forest map were cross checked against the very high resolution imagery recorded between 2012 and 2015. No major deviations were detected, this is likely because the boundary between forest and non-forest is readily apparent in 30 m resolution imagery, and it is difficult for a trained observer to be mistaken regarding the distinction between forest and non-forest at that scale.

Mapping of logging roads between 1983 and 2014 in Wawoi Guavi

In order to map the logging roads built successively in the Wawoi Guavi logging concessions, logging roads were digitised manually in successive Landsat images. Each road was digitised in the Mapinfo GIS the first time it became apparent in the images. Logging roads first became apparent in 1983, hence 1983 was deemed the first year of logging. A logging road was assumed to have been built in the year it became apparent in the imagery or earlier, with 1983 being the first year of logging. The following Landsat images were used to digitise roads in that concession:

Satellite	Path	Row	Year	Day (Julian calendar)
Landsat 4	99	65	1983	82
Landsat 4	99	65	1984	53
Landsat 5	99	65	1987	325
Landsat 5	99	65	1989	10
Landsat 5	99	65	1989	346
Landsat 5	99	65	1989	909
Landsat 5	99	65	1990	108
Landsat 5	99	65	1992	3
Landsat 5	99	65	1992	19
Landsat 5	99	65	1994	39
Landsat 5	99	65	2000	49
Landsat 7	99	65	2001	291
Landsat 7	99	65	2002	54
Landsat 7	99	65	2003	9
Landsat 7	99	65	2004	4
Landsat 5	99	65	2005	6
Landsat 8	99	65	2013	172
Landsat 8	99	65	2013	268
Landsat 8	99	65	2013	364
Landsat 8	99	65	2014	79
Landsat 8	99	65	2014	95

A logging radius for each of the years 1984, 1989, 1994, 2005, and 2014 were created using the same methods used to generate the log radius for 2014 in the above section 'Mapping of logged area 2002-2014'. The area of forest within the logging radius in each of the years was assumed to have been logged in that year or earlier.

Assessment of deforestation for Plantations

Areas of deforestation that occurred within currently established timber or agricultural plantations were deemed to have been cleared to create the plantation. Only areas that were forest in 2002 and were replaced by plantation by 2014 were included as deforestation. Clearing within plantations established prior to 2002, such as occurs when the plantation is harvested, were not included within deforestation statistics.

Assessing forestry-related deforestation

Any area of deforestation in the period 2002-2014 within the mapped timber extraction radius and not associated with industrial agriculture or mining, was deemed to be forestry related. These areas were overwhelmingly logging roads, although deforestation for log ponds, and clearing in and around logging camps were also included.

Assessment of commercially accessible forests

The same map of commercially accessible forests created for the previous State of the Forests report (Shearman *et al.*, 2008) was used in the present assessment. Areas of polygonal karst, slopes too steep for mechanized logging were delineated as physically 'inaccessible'. Forests growing on polygonal karst were identified using a landform map and the satellite imagery used to create the 2002 vegetation map (Shearman *et al.*, 2008). Slopes too steep to log were deemed as those over 25°, and were mapped using a calibrated version of the Shuttle Radar Topography Mission (SRTM) digital elevation model (Shearman *et al.*, 2008). Areas of forest too small to support a commercial logging operation were deemed to be economically 'inaccessible'. A conservative size limit of 50,000 ha was used to define commercially accessible forests, and physically accessible forests less than 50,000 ha in size were deemed to be 'inaccessible' (Shearman *et al.*, 2008).

Determining change rates

We estimated recent change rates by modelling annual clearance in the period 2002-2014 using timber exports. The total area logged and cleared due to forestry was apportioned to individual years over that time period using the volume of timber exported from logging concessions in that year. Thus it was assumed that those years which saw a higher volume of timber exported also saw a proportionally higher area logged or cleared. The volume of timber exported was obtained from Bank of PNG annual reports. For non-forestry related deforestation, the total area cleared was divided evenly between each of the 12 years. We then estimated the recent forest change rate as the percentage of 2013 forest area cleared or degraded in the 2013-2014 period.

Assessing active and inactive concessions

The boundary of all current and proposed Papua New Guinea Forest Authority (PNGFA) logging concessions were overlaid on our 2014 vegetation map and logging radius. Any concession in which logging had occurred 1972-2014 was deemed to be 'active', and any concession in which no logging activity had been recorded 1972-2014 was deemed to be inactive.

Assessing remaining timber volumes in logging concessions

Remaining timber stocks (in m^3) in logging concessions in each province were assessed by multiplying the 2014 area (in hectares) of unlogged commercially accessible forest in that province by the harvest intensity (in $m^3\ ha^{-1}$). A harvest intensity of 15 $m^3\ ha^{-1}$ was used to assess the average remaining timber volumes. A harvest intensity of 10 $m^3\ ha^{-1}$ was used to assess the lower limit of remaining timber volumes, and a harvest intensity of 20 $m^3\ ha^{-1}$ was used to assess the upper limit of remaining timber volumes (see full table in Annex 2).

Assessing change in bioclimatic regions in PNG

The area of rainforest cleared and degraded 2002-2014 within PNG's bioclimatic regions was also assessed. The delineation of 11 bioregions described in Shearman & Bryan (2010) was used as the boundary defining each region. These were: The Sepik-Ramu-Markham basin; the Fly-Gulf region; the Central Highlands; the Huon Peninsula and Adelbert Ranges; the Owen Stanley Ranges; The South-East Papua Lowlands; the Bowutu Ultramafic Belt; the East Papua Islands; D'Entrecasteaux Islands; the Southern Bismarck Island Arc, and the Northern Bismark Island arc. The location of the 11 regions is shown in Annex 2.

Each region was further divided into separate climatic and altitudinal zones. There were four rainfall categories (low, moderately low, moderately high and high); and three altitude categories (upper montane, lower montane, lowland). Full details of each zone can be found in Shearman & Bryan (2010). Deforestation and forest degradation detected 2002-2014 was measured inside each region.

Assessing carbon stocks and potential emmissions through logging at Kamula Doso

The volume of carbon stored in the forests of Kamula Doso was estimated by multiplying the area of forest in 2014 (ha) (measured in this study) by the average carbon (tonnes per hectare) stored in unlogged forests in Kamula Doso. Carbon was converted to carbon dioxide equivalents using a conversion factor of 44/12. The average forest carbon stored in unlogged forests at Kamula Doso was obtained from Bryan (2012). Bryan (2012) measured forest biomass in the neighbouring Makapa logging concession, in the same forest type present at Kamula Doso. A conversion factor of 0.5 was used to convert forest biomass to carbon.

The volume of carbon potentially released through logging was estimated by multiplying the area of commercially accessible forest 2014 in Kamula Doso (ha, measured in this study) by the average volume of carbon (in tonnes per hectare) released during the first harvest of a typical selective logging operation in the region. Carbon was converted to carbon dioxide equivalents using a conversion factor of 44/12. Bryan (2012) and Bryan *et al.*, (2010) measured the forest biomass lost after logging in the neighbouring Makapa concession. A conversion factor of 0.5 was used to convert forest biomass to carbon. The following parameters derived from Bryan (2012) were used to estimate carbon stocks and losses at Kamula Doso:

Annex1 Table 1. Total biomass (live above ground, standing dead, lianas, below ground, litter, coarse woody debris) stored in unlogged forests and potentially released through logging at Kamula Doso (from Bryan (2012), and carbon dioxide (CO_2) equivalent in tonnes per hectare.

Parameter	Total biomass (t ha^{-1})	CO2 (t ha^{-1})
Unlogged forest	372	682
Released through logging (first harvest)	120	220

Annex1 Table 2. Total carbon and carbon dioxide equivalent (millions of tonnes) stored in Kamula Dosos forests (all, and commercially accessible only), and potentially released if logging were to go ahead derived from Bryan (2012).

Parameter	Total carbon (millions tonnes)	Total CO_2 (millions tonnes)
Stored in All forest	131.2	481.0
Stored in Accessible forests	130.8	479.5
Potentially released through logging	42.2	154.8

Annex 2

Ancillary material

The change assessment of Special Agriculture and Business Leases (SABLs) measured the area of forest (logged and unlogged) in 2002 and in 2014 inside 52 of the largest SABLs. Rainforest change 2002-2014 measured the expansion of forest degradation and the expansion of deforestation inside individual SABLs. Forest degradation 2002-2014 was calculated as the area of logged forest in 2014 minus the area of logged forest in 2002. Deforestation 2002-2014 was calculated as the Total area of forest 2002 minus the Total area of forest 2014. Total change 2002-2014 was measured as the area deforested 2002-2014 plus the area degraded 2002-2014. In some SABLs, the area of older logged forests (1972-2002) cleared between 2002 and 2014 was greater than the area of newly logged forest (2002-2014), meaning there was an overall decline in the area of logged forests between 2002 and 2014. In these SABLs, forest degradation 2002-2014 was reported as 0.

Ancillary Table 1. Forest area and change in the period 2002-2014 in each of 52 SABLs.

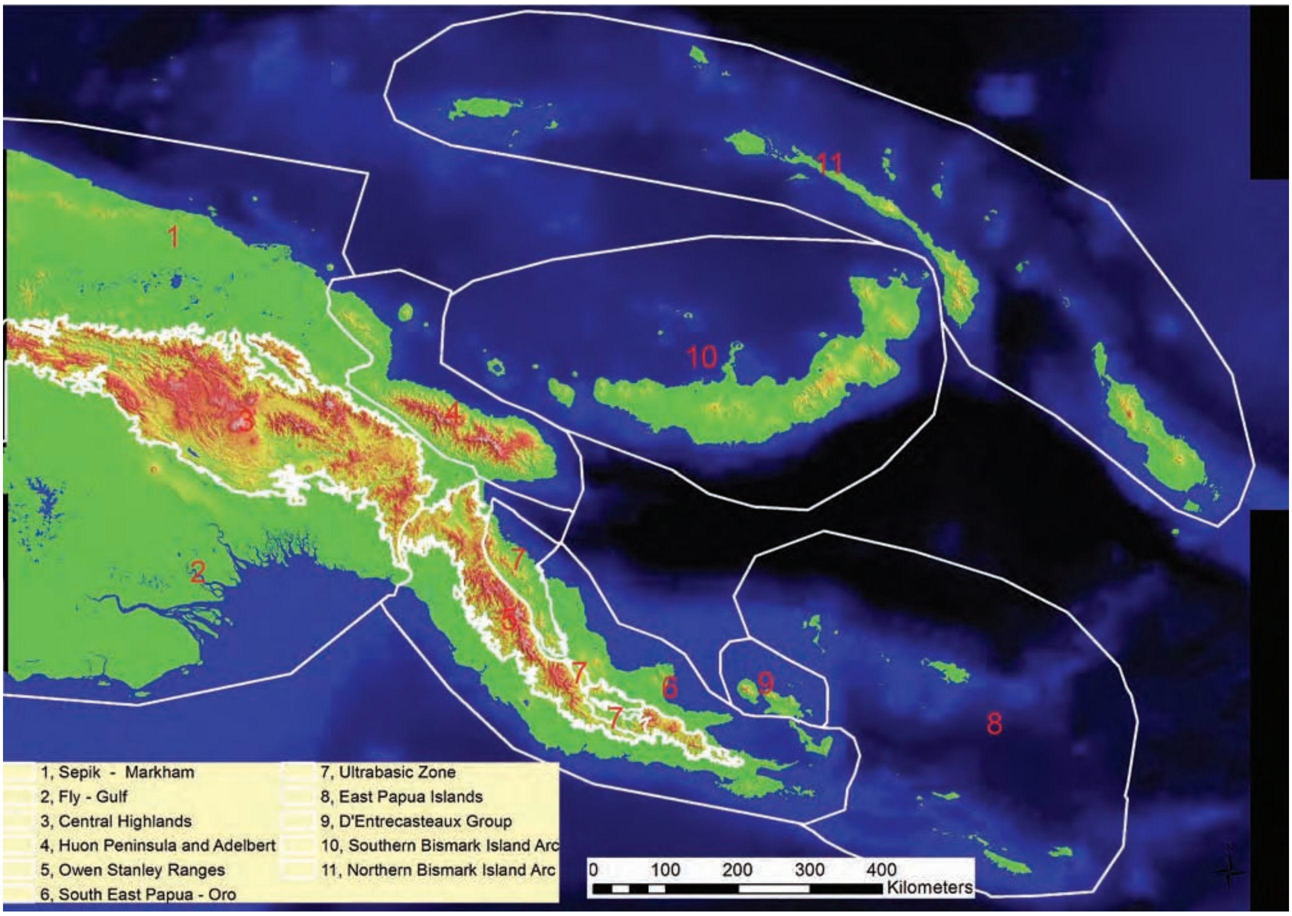
				Rainforest 2014					Rainforest change 2002-2014				
									Deforestation				
Grantee	**Portion**	**Province**	**Land area**	**Total**	**Unlogged**	**Logged**	**Logged 1972-2002 (%)**	**Logged 2002-2014 (%)**	**Plantation**	**Forestry**	**Other**	**Tot.**	**Total change (deforest. and degrad.)**
ABEDA AGRO FOREST LIMITED	409C	CEN	111	91	21	70	93	7	0	7	0	7	7
AINBAI-ELIS HOLDING LIMITED	40C	WSK	228	204	181	23	40	60	1	2	0	4	18
AIOWA OIL PALM LIMITED	6C	GUL	123	65	47	18	21	79	0	2	0	2	16
AKIVRU LIMITED	398	WNB	60	42	0	42	100	0	0	0	0	0	0
BAINA AGRO-FOREST LIMITED	29C	CEN	413	384	303	81	9	91	2	3	0	5	78
BEWANI PALM OIL DEVELOPMENT LTD	160C	WSK	1,145	851	171	680	69	31	48	24	0	72	233
BRILLIANT INVESTMENT LTD	146C	ESK	250	145	3	143	49	51	9	11	0	20	87
CASSAVA ETAGON HOLDINGS LTD	884C	NIR	278	53	0	53	100	0	0	0	0	0	0
CENTRAL NEW HANOVER LIMITED	887C	NIR	569	338	176	162	3	97	0	43	4	48	203
EAST WAII OIL PALM LIMITED	5C	GUL	209	158	24	135	98	2	0	1	0	1	3
EMIRAU TRUST LTD	53C-58C	NIR	33	17	17	0	0	0	0	0	0	0	0
FOIFOI LIMITED	9C	WES	335	273	0	273	100	0	0	2	0	2	2
GODAE LAND GROUP INC	7C	WES	149	95	2	93	100	0	0	0	0	0	0
GOGORANTO LIMITED	33	WNB	89	61	1	60	96	4	0	0	0	0	2
HAUBAWE HOLDINGS LIMITED	8C	WES	133	119	0	119	100	0	0	3	0	3	3
IVAGA OUROUINO-MUSENAMTA LIMITED	397	WNB	103	71	0	71	100	0	0	1	0	1	1
KAVUN LIMITED	34	WNB	67	49	16	33	98	2	0	0	0	0	1
KOARU RESOURCE OWNERS COMPANY LTD	323C	GUL	596	451	451	0	0	0	0	0	17	17	17
KONEKARU HOLDINGS LTD	2465C	CEN	5	0	0	0	0	0	0	0	0	0	0

				Rainforest 2014					Rainforest change 2002-2014				
									Deforestation				
Grantee	Portion	Province	Land area	Total	Unlogged	Logged	Logged 1972-2002 (%)	Logged 2002-2014 (%)	Plantation	Forestry	Other	Tot.	Total change (deforest. and degrad.)
KONEKARU HOLDINGS LTD	2466C	CEN	1	0	0	0	0	0	0	0	0	0	0
LA-ALI INVESTMENTS LIMITED	5C	WES	74	59	0	59	100	0	0	0	0	0	0
MEKEO HINTERLANDS HOLDINGS LIMITED	45C	CEN/GUL	1,156	957	957	0	0	0	0	0	1	1	1
MUDAU INVESTMENT LIMITED	6C	WES	105	94	8	85	96	4	0	2	0	2	4
MUSA VALLEY MANAGEMENT COMPANY LIMITED	17C	ORO	3,207	1,947	1,947	0	0	0	0	0	21	21	21
NAKIURA INVESTMENT LIMITED	198C	ENB	160	86	34	51	21	79	16	8	0	24	55
NORTH EAST WEST INVESTMENTS LTD (NEWIL)	1C	WES/SHY	7,872	7,035	7,033	2	72	28	0	0	10	10	10
NORTH EAST WEST INVESTMENTS LTD (NEWIL)	27C	WES	1,493	1,262	1,262	0	0	100	0	4	19	23	23
NUKU RESOURCES LTD	26C	ESK/WSK	2,355	1,502	1,502	0	0	0	0	0	17	17	17
NUNGAWA RAINFOREST MANAGEMENT ALLIANCE LIMITED	55C	ESK/WSK	963	614	614	0	0	0	0	0	5	5	5
OSSIMA RESOURCES LIMITED*	163C	WSK	311	261	97	163	17	83	4	14	0	19	153
POLOPO LIMITED	35	WNB	84	41	0	41	99	1	0	0	0	0	0
POMATA INVESTMENT LIMITED	196C	ENB	146	81	38	43	32	68	29	4	0	33	56
PULIE ANU PLANTATION LTD	396C	WNB	460	304	21	284	91	9	0	3	0	3	28
PURARI DEVELOPMENT ASSOCIATION INC	8C (GP)	GUL/CHI	7,304	4,723	4,459	264	43	57	0	14	49	63	213
RAKUBANA DEVELOPMENT LTD	871C	NIR	257	202	63	139	84	16	0	7	0	7	25
RALOPAL INVESTMENT LIMITED	197C	ENB	111	84	79	5	65	35	0	0	0	1	2
RERA HOLDINGS LIMITED	2C	ENB	685	434	431	3	100	0	0	0	1	1	1
SEPIK OIL PALM PLANTATION LIMITED	144C	ESK	1,156	656	397	259	0	100	2	12	4	18	277
TABUT LIMITED	885C	NIR	126	83	0	82	100	0	0	3	0	3	3
TORIU TIMBERS LIMITED	903C	ENB	424	318	145	173	32	68	2	17	0	19	131

				Rainforest 2014					Rainforest change 2002-2014				
									Deforestation				
Grantee	Portion	Province	Land area	Total	Unlogged	Logged	Logged 1972-2002 (%)	Logged 2002-2014 (%)	Plantation	Forestry	Other	Tot.	Total change (deforest. and degrad.)
TORIU TIMBERS LIMITED	904C	ENB	114	73	20	53	19	81	3	3	0	6	48
TOSIGIBA INVESTMENT LIMITED	14C	WES/SHY	6,343	5,581	5,581	0	0	0	0	0	120	120	120
TUMU TIMBERS DEVELOPMENT LIMITED	1C	WES	4,645	4,140	4,140	0	0	100	0	0	41	41	41
UMBUKUL LIMITED	886C	NIR	246	183	79	104	92	8	0	2	0	3	10
UNUNG SIGITE LIMITED	27C	ENB	130	119	118	0	62	38	0	0	1	1	1
URASIR RESOURCES LIMITED	16C	MAD	1,111	914	913	1	0	100	0	0	10	10	11
VANIMO JAYA LTD & ONE-UNI DEVELOPMENT CORPORATION	248C	WSK	474	336	272	64	0	100	20	4	1	25	89
WAMMY LIMITED	27C	WSK/ESK	1,133	594	594	0	0	0	0	0	3	3	3
WEST MAIMAI INVESTMENTS LTD & YANGKOK RESOURCES LIMITED & PALAI RESOURCES LTD (JOINT TENANTS)	594C	WSK/ESK	1,562	1,018	1,018	0	0	0	0	0	6	6	6
WOWOBO OIL PALM LIMITED	4C	GUL	238	204	13	191	100	0	0	0	0	0	0
YUMU RESOURCES LTD	30C	CEN	951	835	743	93	65	35	0	1	1	2	34
Unnamed	323C	GUL	131	37	37	0	0	0	0	0	1	1	1
TOTAL			**50,422**	**38,242**	**34,026**	**4,216**	**65**	**35**	**136**	**200**	**334**	**670**	**2,047**

Ancillary Table 2. Remaining timber volumes in PNG's logging concessions 2014. Lower, upper and average estimates are shown.

		Timber volume 2014 m^3		
Province	**Unlogged accessible forest 2014 (km^2)**	**Lower (10 $m^3\ ha^{-1}$)**	**Upper (20 $m^3\ ha^{-1}$)**	**Average (15 $m^3\ ha^{-1}$)**
Western *(including Kamula Doso)*	25,462	25,462,031	50,924,062	38,193,047
Western *(excluding Kamula Doso)*	18,434	18,434,457	36,868,914	27,651,685
Gulf	8,617	8,617,000	17,234,000	12,925,500
Central	2,663	2,663,400	5,326,800	3,995,100
Milne Bay	1,433	1,432,645	2,865,290	2,148,967
Oro	4,357	4,357,063	8,714,126	6,535,594
Morobe	842	842,251	1,684,501	1,263,376
Madang	3,256	3,255,751	6,511,503	4,883,627
East Sepik	1,520	1,520,060	3,040,121	2,280,091
West Sepik	7,413	7,413,125	14,826,250	11,119,687
Mainland coastal region	**55,563**	**55,563,326**	**111,126,652**	**83,344,989**
Mainland coastal *(excluding Kamula Doso)*	(48,536)	(48,535,752)	(97,071,504)	(72,803,628)
Southern Highlands / Hela	2,504	2,504,003	5,008,006	3,756,005
Enga	140	140,000	280,000	210,000
Western Highlands / Jiwaka	512	511,754	1,023,507	767,630
Chimbu	0	0	0	0
Eastern Highlands	0	0	0	0
Highlands region	3,156	3,155,757	6,311,513	4,733,635
Mainland total	**58,719**	**58,719,083**	**117,438,165**	**88,078,624**
Mainland *(excluding Kamula Doso)*	(51,692)	(51,691,508)	(103,383,017)	(77,537,263)
Manus	478	478,000	956,000	717,000
New Ireland	574	543,728	1,087,456	815,592
East New Britain	1768	1,768,000	3,536,000	2,652,000
West New Britain	3746	3,746,000	7,492,000	5,619,000
Bougainville	490	490,429	980,859	735,644
Islands region	**7,026**	**7,026,157**	**14,052,314**	**10,539,236**
TOTAL PNG	**65,745**	**65,745,240**	**131,490,480**	**98,617,860**
TOTAL PNG *(excluding Kamula Doso)*	**(58,718)**	**(58,717,666)**	**(117,435,331)**	**(88,076,498)**



Ancillary Figure 1. Location of bioregions in Papua New Guinea from Shearman & Bryan (2010).

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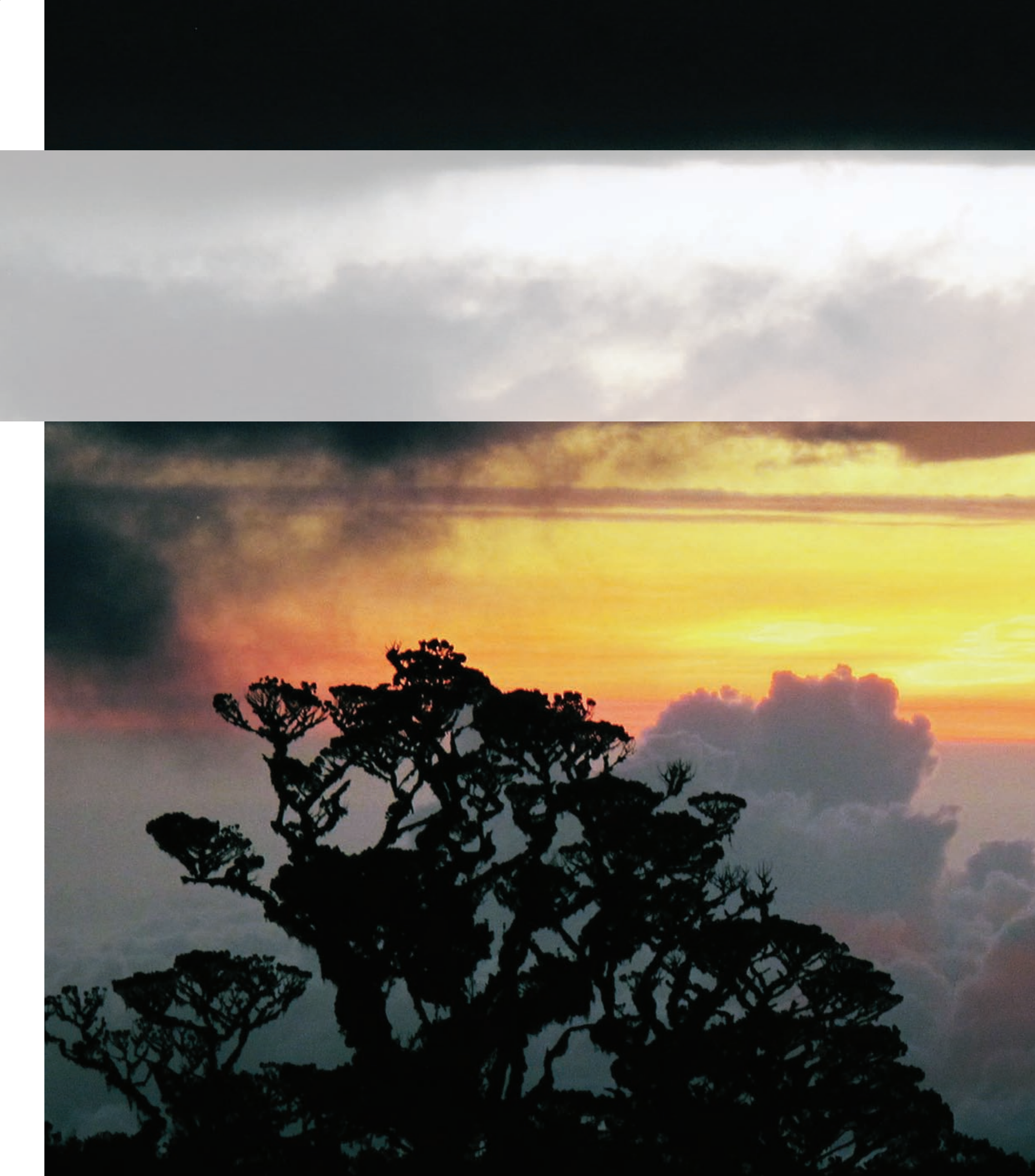
Coffee Plantation, Waghi Valley

Log Pond, Vanimo

Lower Sepik River

Bam Island, East Sepik Province



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