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# Native forest management in Papua New Guinea: advances in assessment, modelling and decision-making

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# Native forest management in Papua New Guinea: advances in assessment, modelling and decision-making

*Editors*: Julian C. Fox, Rodney J. Keenan, Cris L. Brack and Simon Saulei

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Cover: Large-scale harvesting offers temporary employment for communities, but monetary returns to the community and ongoing benefits can be limited. (Photo: Joe Pokana)

# Foreword

Forests in Papua New Guinea (PNG) are of considerable cultural, biological and economic value. Held under customary ownership by local communities and tribal groups, the forests play a vital role in sustaining traditional subsistence livelihoods, supporting a rich endemic biodiversity and contributing to the national economy and development. However, forest management in PNG faces many challenges, including improving the sustainability of large-scale logging, enhancing returns from forest management and reducing greenhouse gas emissions associated with deforestation. For these reasons, the Australian Centre for International Agricultural Research (ACIAR) has supported collaborative research between Australian forest scientists and PNG institutions and community groups on improving the management of secondary forests.

This report reviews the historical context of forest management and the recent focus on tropical forest-based climate-change mitigation in PNG, and identifies challenges and priorities. Advances in the assessment of timber, carbon stocks and biodiversity, as well as in the quantitative understanding of forests through modelling, are described in order to provide a scientific basis for forest-management decision-making at both the community and the government level. The report makes a major contribution through the estimation of carbon dioxide emissions from logging, soil carbon stocks, carbon sequestration rates for secondary forests and financial returns from small-scale community forestry.

Many of the chapters contained within the report were presented at a final project workshop held at the Papua New Guinea Forest Research Institute, Lae, in October 2010. Native forest management in PNG is increasingly subject to international and local interest, and forest-management standards, institutional capacity and returns to landowners need to be improved. Sustainable forest management requires a sound scientific understanding of the forest resource. This compilation of work, which strengthens the scientific basis for sustainable native forest management in PNG, is timely.

Nick Austin
Chief Executive Officer
ACIAR

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# Abbreviations

| | |
|---|---|
| **AAC** | annual allowable cut |
| **ACIAR** | Australian Centre for International Agricultural Research |
| **AGLB** | above-ground live biomass |
| **AO** | area overlap |
| **APA** | area potentially available |
| **APFC** | Asia Pacific Forestry Commission |
| **ASTER** | Advanced Spaceborne Thermal Emission and Reflection Radiometer |
| **BA** | basal area |
| **BAF** | basal area factor |
| **BAU** | business as usual |
| **C** | carbon |
| **CMU** | central marketing unit |
| **$CO_2$** | carbon dioxide |
| **COP** | Conference of the Parties |
| **CRI** | combined relative importance |
| **DBH** | diameter at breast height |
| **DCD** | diameter – crown diameter |
| **DDI** | distance-dependent indexes |
| **DEM** | digital elevation model |
| **DH** | diameter–height |
| **DMH** | diameter – merchantable height |
| **DWSR** | distance-weighted size ratio |
| **EMV** | expected monetary value |
| **ENSO** | El Niño Southern Oscillation |
| **FAO** | Food and Agriculture Organization of the United Nations |
| **FORCERT** | Forest Management and Product Certification Service |
| **FPC** | foliage projected cover |
| **FPCD** | Foundation for People and Community Development |
| **FRI** | Forest Research Institute |
| **FSC** | Forest Stewardship Council |
| **GHG** | greenhouse gas |
| **HBM** | hierarchical Bayesian model |
| **IPCC** | Intergovernmental Panel on Climate Change |
| **ITTO** | International Tropical Timber Organization |
| **IUCN** | International Union for Conservation of Nature and Natural Resources |
| **K** | kina |
| **LULUCF** | land use, land-use change and forestry |
| **MEP** | minimum export price |
| **Mha** | million hectares |
| **$Mm^3$** | million cubic metres |
| **MPI BC** | Max Plank Institute of Biogeochemistry |
| **MRV** | measurement, reporting and verification |
| **MV** | merchantable (timber) volume |
| **NCAS** | National Carbon Accounting System |
| **NGO** | non-government organisation |
| **OCCD** | Office of Climate Change and Development |
| **OCCES** | Office of Climate Change and Environmental Sustainability |
| **PAR** | participatory action research |
| **PDM** | pebble distribution method |
| **PMCP** | Planning Monitoring and Control Procedures |
| **PNG** | Papua New Guinea |
| **PNGFA** | Papua New Guinea Forest Authority |
| **PNGFRI** | Papua New Guinea Forest Research Institute |
| **PSP** | permanent sample plot |
| **REDD** | reducing emissions from deforestation and forest degradation |
| **REDD+** | reducing emissions from deforestation and forest degradation and enhancement of forest carbon stocks |
| **RIL** | reduced-impact logging |
| **SABL** | Special Agricultural and Business Lease |
| **SAR** | synthetic aperture radar |
| **SD** | standard deviation |
| **SFM** | sustainable forest management |
| **SOC** | soil organic carbon |

| | |
|---|---|
| **SWIR** | short-wave infrared |
| **TIR** | thermal infrared |
| **UNFCCC** | United Nations Framework Convention on Climate Change |
| **VCS** | Voluntary Carbon Standard |
| **VDT** | Village Development Trust |
| **WMA** | Wildlife Management Area |
| **VNIR** | visible and near-infrared |
| **WWF** | World Wide Fund for Nature |

# Introduction

# Native forest management in Papua New Guinea: an introduction

**Rodney J. Keenan[1,2], Julian C. Fox[1], Cris L. Brack[3] and Simon Saulei[4]**

The total land area of Papua New Guinea (PNG) is 46.3 million ha (Mha), with about 33 Mha covered by closed natural forest. The forests of PNG are structurally diverse and complex, ranging from dense lowland tropical forests (Figure 1) to montane forests up to 4,000 m (Figure 2). They have been subject to limited scientific investigation. With approximately 11,000 different plant species, the tropical forests and freshwater wetlands of PNG are considered to be of similar biological and conservation importance to those in the Amazon and Congo Basin. Most forests in PNG are under customary ownership by local communities, tribal groups or individuals, and play a vital role in sustaining the traditional subsistence livelihoods of most of the population. Forest resources are also a major contributor to the national economy, with the sector employing about 10,000 people. Log exports were valued at over US$170m in 2006 and contributed some 200m kina (K200m) in export duties, royalties and taxes (PNGFA 2009).

Yosi et al. (2011) describe the historical development of forest management in PNG and identify current issues facing the sector. For example, current forest-harvesting operations do not generally meet international standards or deliver long-term benefits for landowners. Further, financial returns to resource owners have fallen substantially in real terms over the past decade and are often too small to impact on living standards, with employment and other 'spin-off' benefits usually being taken by outside workers. Better management of forest resources is required if local communities are to realise the benefits from forest utilisation. Basic health and education services are lacking in many areas of PNG, which is ranked 149th of 177 countries in the UN's human development index.

The current level of forest harvesting by the log-export industry cannot be sustained, and accessible primary forest is likely to be logged in the next 20–30 years (Filer et al. 2009; Shearman et al. 2009). There is concern about the recovery of forests after harvesting and the potential of forests to provide timber or other community needs into the future (Shearman et al. 2009). With a high level of forest exploitation and poor returns to resource owners, it is little wonder that the credibility of forest management in PNG has been questioned (Laurance et al. 2010).

Alternative forest-management systems based on stronger community control and involvement with management, as well as potential remuneration for other forest values such as carbon (C), have the potential to provide greater returns to local landowners, build skills and capacity in business management and marketing, and foster greater community resilience in response to future threats such as climate change.

Forest management in PNG faces many challenges—it finds itself in transition from being driven by harvesting logs from primary forest for export to an increased focus on secondary forests, regrowth and plantations; domestic processing of forest products; and a growing importance of other forest values such as C and biodiversity. Native forest timber production is increasingly subject to international and local scrutiny, and forest-management standards need

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**Figure 1.** Lowland primary tropical forest in the Sogi community area near Madang (Photo: Julian Fox).

**Figure 2.** Montane forest at 3,500 m above sea level in the vicinity of Mt Wilhelm (Photo: Julian Fox).

to be improved to meet basic management requirements and international certification.

Remuneration for other forest values such as C has generated much interest in PNG, particularly as an alternative income source to large-scale timber harvesting. Forests play an important role in stabilising rising atmospheric carbon dioxide ($CO_2$) concentrations through the absorption and sequestration of carbon in tree biomass, as well as sequestration in dead trees, soil and harvested timber. In particular, tropical forests have been recognised for their ability to absorb and store C in forest biomass—an initiative under the UN Framework Convention on Climate Change includes reducing $CO_2$ emissions in developing tropical countries towards international targets using REDD+ (reducing emissions from deforestation and forest degradation, and enhancement of forest carbon stocks). Fox et al. (2011a) introduces REDD+ and describes activities toward the mechanism in PNG. REDD+ can potentially offer economic, environmental and social benefits for PNG and, if implemented appropriately, could provide wider social and economic opportunities for indigenous people.

Advances in the assessment of the wide range of goods, services and values in complex tropical forests such as those found in PNG, as well as domestic processing and payment for these goods and environmental services, are necessary to achieve the potential community benefits from improved forest management. New methods are also required for modelling growth and yield to ensure sustainable timber production, and for C dynamics to understand the potential influence of forest management. Forest-management systems that improve community-based management and decision-making need to be investigated and evaluated.

The PNG Forestry Act 1991 prescribes a 1% (by area) systematic stripline forest inventory methodology to support national, provincial and forest-level planning. This is problematic as the approach is inefficient and likely to produce biased resource estimates that are not representative of the forest as a whole. In this volume Brack (2011) discusses the context of the 1% stripline as used in PNG and reviews alternative modern forest inventory approaches such as multistage and multiphase sampling. He presents examples of modern forest inventory techniques such as variable-radius sampling, and Fox et al. (2011b) demonstrate an application for the Sogi community forest that integrates stratified random variable-radius plots with optical remote sensing data. This latter method provides estimates and maps of merchantable timber volume and above-ground live biomass (AGLB) for community-based forest planning at a considerably lower cost than using traditional methods. While the combination of ground plots and optical remote sensing is powerful and cost-effective, optical data have limitations in the tropics due to persistent cloud cover. Williams et al. (2011) explore the information content of radar remote sensing of tropical forests, which is unaffected by cloud cover, provide examples of forest classification in the Kokoda area using an airborne synthetic aperture radar (SAR) system, and discuss how it can be used for forest biomass estimation. Modern forest inventory combined with remote sensing data for accurate forest assessment is important for improving forest management in PNG, and will be integral in quantifying C stock changes for reporting in mechanisms such as REDD+.

For effective management of timber or C resources, forest managers need models of forest growth and yield under different forms of management. The work of Alder (1998) provided some initial model development based on preliminary data from permanent sample plots (PSPs). In this volume Fox et al. (2011c) present species-based individual-tree growth models based on longer term measurements from the extensive PSP system established and managed by the PNG Forest Research Institute (FRI) with support from the Australian Centre for International Agricultural Research (ACIAR). These individual-tree models characterise the competitive, growth, mortality and recruitment dynamics of individual trees. They can be used for optimising the design of silvicultural systems to meet different needs, and for generating accurate growth and yield estimates, which are fundamental to sustainable forest management. Dynamics research of tropical forest stands poses a challenge because tropical forests are typically structurally complex and highly species rich. Zimmer and Fox (2011) take a different approach from long-term field measurement data and explore dendrochronology (the study of tree rings) to understand tree growth and forest dynamics in high-elevation forests in PNG.

REDD+ and voluntary C agreements have generated much interest in PNG. However, significant policy, institutional and technical challenges need to be overcome before REDD+ becomes operational. Technical challenges facing REDD+ implementation include: estimation of forest C stock in different forest


International scrutiny on tropical forest management and climate-mitigation initiatives such as REDD+ has highlighted the need for forest assessment. Here, Heidi Zimmer works with Kgwan community members from Simbu province on tree core samples that can be used to reconstruct historical forest growth (Photo: Julian Fox). See Zimmer and Fox (2011).

strata and C pools (Gibbs et al. 2007); and estimation of changes in these stocks associated with forest harvesting (Kauffman et al. 2009). The largest forest C pool is in AGLB, and this has been estimated for PNG in Fox et al. (2010). Fox et al. (2011d) then present analysis of changes in AGLB due to harvesting, fire and growth. Other important and rarely measured forest C pools include both soil C and C in litter on the forest floor. Nimiago (2011) and Nimiago et al. (2011) describe the commencement of soil C and litter measurement programs, respectively, for PNG, and provide early results.

Aside from estimating forest C pools and their dynamics, REDD+ and voluntary C agreements will require accounting systems that incorporate the dynamics of all C pools affected by forest harvesting. Fox and Keenan (2011) present results from a national C accounting framework developed to model the $CO_2$ emissions associated with selective harvesting in PNG. Building on this, Coote and Fox (2011) use scenario analysis to explore forest-management options for PNG and their implications for $CO_2$ emissions. Hunt (2011) examines methodologies for assessment of the emissions abated by REDD+ proposals and the opportunity costs of doing so. This body of work contributes to the scientific basis for PNG's participation in climate-mitigation initiatives such as REDD+.

Forests play a vital role in sustaining traditional subsistence livelihoods in PNG and are mostly under customary ownership by local communities, tribal groups or individuals. Many communities are seeking to take more control and manage their forest resources to provide goods for market or services. Community forest management presents new economic, technical and social challenges. Grigoriou et al. (2011) examine some of the economic challenges and determine the feasibility of small-scale community forestry in PNG. Effectively integrating community decision-making in the forest-management process is an important social challenge. Yosi et al. (2011) demonstrate a method for evaluating community forest-management scenarios that may result in improved community decision-making. Communities in PNG interact with their forest and biodiversity, and Bastyte et al. (2011) examine this interaction for communities in Madang province.

Sustainable management of natural forests is considered an integral part of the strategy for future economic development of PNG. The National Forest Policy states that the forest resource will be managed for the broad range of commercial benefits and non-commercial values it can provide for present and future generations. However, sustainable forest management requires a sound scientific understanding of the forest resource. This compilation of work funded by ACIAR is timely, due to increasing international and local scrutiny of native forest management in PNG. Advances in forest research described in this volume can provide the basis for improved management in PNG, particularly by community owners for a wider range of goods and services.

The importance of sound field measurements for informing sustainable forest management and climate-mitigation initiatives such as REDD+ cannot be understated. Here, community members from Sogi (near Madang) take a diameter measurement above the buttress of a tree in their tribal lands (Photo: Julian Fox). See Fox et al. (2011b).

Community forest management often empowers and includes the whole community. Here, young boys from the Sogi community carry sawn timber to the roadside for export to Australia (Photo: Julian Fox). See Fox et al. (2011b).

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# Forest management in Papua New Guinea: historical development and future directions

**Cossey K. Yosi[1,2*], Rodney J. Keenan[3,4] and Julian C. Fox[3]**

*Abstract*

Forest management worldwide is increasingly focused on values such as biodiversity conservation, carbon, water and recreation as well as timber production. Ownership and governance arrangements are also changing, with an increase in private ownership of forest resources that is focused on timber production and devolution of management and control to the community level. Forest management is particularly challenging for tropical forests due to their diverse composition and structure and a wide range of stakeholder expectations and requirements. New management approaches and policy directions are required to meet these various challenges.

Papua New Guinea (PNG) has a significant area of tropical forest composed of a wide range of forest types and environments. Most of the forest is under the customary ownership of indigenous people, with a similarly high ethnic and cultural diversity. Local people have used forest land and resources for thousands of years for subsistence and cultural needs. For the past 20 years, much of the focus of formal forest management and policy in PNG has been on large-scale conventional harvesting to meet national requirements for economic development, with little attention given to community-level forest management. The current management system is considered by many to be unsustainable and, as commercial timber resources from primary forests are exhausted, there have been few examples of future management plans for cutover forests. This has resulted in extensive cutover forest areas being left to degrade over time.

This paper presents a review and overview of the stages of development of forest management in PNG and the current state of forest resources. It is argued that a new policy approach is required for forest management that reflects changing local and international expectations, and current and future requirements, for forest management and forest resources. This should include consideration of the future production capacity of cutover and degraded forests as well as development of the capacity of local forest-owner communities to participate in small-scale forest management and utilisation, for example through management systems that are compliant with the requirements of certification bodies.

## Introduction

Papua New Guinea has abundant natural resources with a very diverse ecosystem comprising over 11,000 plant species. However, the country is facing many challenges in terms of resource development as the government looks for alternative ways to improve and sustain the livelihoods of a large rural population. PNG has approximately 33 million hectares (Mha) of forests. In 1982 it was estimated that 75% of PNG's land surface was covered with forest land, equating to more wood per person than any other country—about 600 m$^3$ per person (Evan 1982). In many communities

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throughout PNG, forests are a part of people's way of life and over 80% of the population depends on them for food, shelter, medicine and other cultural benefits, with 97% of the forests being under customary ownership by individuals or community groups. According to the International Tropical Timber Organization (ITTO) (2006), each citizen of PNG, on average, has rights over approximately 6.4 ha of forest; however, despite this, the majority of indigenous communities are still living in extreme poverty. The forestry sector is the country's third largest contributor to government revenue; for example, in 2003 PNG earned US$126m from the export of tropical timber (ITTO 2006). This revenue has been generated from primary forests.

Due to the fact that most global wood production comes from natural or semi-natural forests rather than plantations, natural forest research and management elsewhere and in PNG remains an important basis to assist sustainable forest management. As accessible primary forests are being exhausted in PNG through commercial timber harvesting and other land uses such as large-scale forest conversion to agriculture and shifting cultivation, future forest management will begin to focus on cutover secondary forests. Shifting cultivation is a traditional method of subsistence farming that contributes to the loss of forest cover.

Given customary ownership arrangements, the future management of cutover forests is likely to be decided by local community groups. A major challenge, therefore, is the development of sustainable management systems for cutover forests that meet the needs of community forest owners.

## Background

### PNG's National Forest Policy

The National Goals and Directive Principles are set out in PNG's Constitution; in particular, the Fourth Goal of the Constitution provides the basis for the country's forest policy, which is to ensure that the forest resources of the country are used and replenished for the collective benefit of all Papua New Guineans now and for future generations. The country's National Forest Policy (the policy) has been designed and formulated to remedy the shortcoming of the previous policy of 1987—to address the recommendations of the Barnett Forest Industry Inquiry of 1989 and a World Bank Review of 1990, and to adjust to new situations in the forestry and forest industry sectors (Ministry of Forests 1991a). The 1989 inquiry into the forest industry, carried out by former national court judge Justice Tos Barnett, uncovered malpractices and corrupt dealings in the timber industry. The policy was approved in 1990. followed by the passing of the Forestry Act in the National Parliament in July 1991 (Ministry of Forests 1991b). The two main objectives of the country's forestry policies are management and protection of the nation's forest resources as a renewable national asset, and use of the nation's forest resources to achieve economic growth, employment creation, participation in industry and increased viable domestic processing.

The Papua New Guinea Forest Authority (PNGFA) is a government statutory body with regulatory and administrative responsibility for the management of the forest sector (ITTO 2006). PNGFA was established in 1991 under the provisions of the Forestry Act sec. 5 (Ministry of Forests 1991b). It succeeded the former Department of Forests, the 19 provincial forest divisions and the Forest Industry Council.

After the approval of the policy and the passing of the Act, new forestry legislation has been put in place (PNGFA 1996a), including the following: Forest Regulation No. 15 1992 was introduced to enable registration of forest industry participants and consultants under the Act; the Forestry (Amendment) Act 1993 provided for a clear administrative function of the PNGFA Board, the National Forest Service through the Managing Director, and the Provincial Forest Management Committees; and The National Forest Development Guidelines were issued by the Minister for Forests and endorsed by the National Executive Council during September 1993. The guidelines established essentially an implementation guide for aspects covered in the 1993 Act, especially in terms of sustainable production, domestic processing, forest revenue, training and localisation, review of existing projects, forest resource acquisition and allocation, and sustainable development.

The National Forest Plan is prepared by the Forest Authority under the Forestry (Amendment) Act 1993 as a requirement under the Act to provide a detailed statement of how the national and provincial governments intend to manage and use the country's forest resources. The National Forest Development Programme under the plan is now under implementation. The PNG Logging Code of Practice was finalised in February 1996 and tabled in Parliament in July 1996 (PNGFA and DEC 1996). The code is inconsistent with the Regional Code proposed at the 1995 Suva Heads of Forestry Meeting, but is more specific to PNG operating conditions and was mandated in July 1997. The 1996 Forestry Regulations, which cover all facets of the industry's procedures and control, were approved by the National Executive Council in 1996, subject to some changes to be finalised later. These regulations provide the legal status for implementation of many of the requirements specified under the Forestry (Amendment) Act 1993.

The Forestry (Amendment no. 2) Act 1996 was passed by Parliament and certified on 11 October 1996. The major amendment relates to the membership of the Board to still have eight members, including the representatives of a National Resource Owners Association and the Association of Foresters of PNG. Since the Forestry Act was first enacted in 1991, it has been amended four times (PNGFA 1996a). The first was in 1993, followed by additional amendments in 1996, 2000 and 2005 (PNGFA 1996a).

## Overview of PNG's forest resources

Papua New Guinea is located in the eastern half of the island of New Guinea and lies 160 km north of Australia. The country comprises both the mainland and some 600 offshore islands, covering a total landmass of about 46 Mha, of which approximately 33 Mha is forested. The forested land is productive and has potential for some form of forest development (PNGFA 1998).

The forests of PNG are widespread and are a valuable long-term national asset. The country's vegetation and forest types have been described in detail (e.g. Paijmans 1975, 1976; Saunders 1993; Hammermaster and Saunders 1995). Papua New Guinea's wide range of floristic composition is a characteristic of the lowland tropical forests. Forest cover in PNG declined at an estimated annual rate of 113,000 ha (0.4%) between 1990 and 2000 (FAO 2005). Reports from PNGFA suggest that PNG's natural forests are being overexploited, with the country's forest area decreasing at a rate of 120,000 ha per year (PNGFA 2003) through harvesting, agricultural activities, mining and other land uses. Current statistics from PNGFA (2007) estimate that, from 1988 to 2007, well over 2 Mha of primary forest were harvested commercially.

## Brief history of forest exploitation in PNG

During World War II timber harvesting from natural forests in PNG commenced, mainly for military purposes. Several years after the war, forestry activities resumed and efforts were then concentrated on producing timber for post-war reconstruction and building. Early commercial timber harvesting started in the

Failed regeneration associated with the Gogol Timber Project has resulted in grasslands in the vicinity of Madang (Photo: Julian Fox).

1950s (Lamb 1990) in the Bulolo area, where a plymill was established to process *Araucaria* logs from natural forest stands. In 1964 a World Bank report indicated extensive forest resources in PNG that warranted large-scale commercial exploitation (Lamb 1990). Following this report, large timber areas in Bougainville and the Gogol Valley in Madang were offered for sale by public tender, and there was an increase in timber areas allocated for harvesting throughout PNG under the Timber Rights Purchase (TRP) arrangement. In 1968 the PNG Administration called for an increase in the production and downstream processing of timber throughout the country. In 1970 the Gogol Timber Project (GTP) became a major pulpwood development project for PNG, with an agreement signed in 1971 between Japan and New Guinea Timbers (JANT). In 1974 JANT shipped the first woodchips from the GTP to Honshu Paper Co. in Japan (Lamb 1990).

Prior to 1980, Australian companies began harvesting in some parts of PNG, and from the 1980s to 1990s there has been extensive harvesting of primary forests, especially by companies from Malaysia and Japan. Currently, the timber industry in PNG is dominated by Asian companies and more than 80% of all timber concessions are controlled by the Malaysian harvesting giant Rimbunan Hijau. According to PNGFA (2007), allocation of new timber concession areas has increased since 2000, including the release of 10 new timber areas for harvesting in 2007. The history of harvesting and the increased allocation of timber concession areas since the 1990s suggests that primary forests in PNG are under extreme pressure from industry, and the area of cutover forests is rapidly increasing (see Shearman et al. 2009a).

### Status of cutover forests

The current rate of harvesting of primary forests is considered unsustainable, and the potential of these forests to either recover or degrade after harvesting is either not well understood or uncertain. In 1992 forest areas included in timber concessions comprised about 5.7 Mha and the total cutover forest area was estimated to be about 850,000 ha (Bun 1992), increasing to an estimated 1 Mha by 1995 (Nir 1995). According to recent PNGFA statistics from 1988 to 2007, the estimated area harvested commercially was over 2 Mha and the timber volume harvested in the form of logs during the same period was over 39 $Mm^3$ (PNGFA 2007).

From 2002 statistics, PNGFA estimated that undisturbed forest in PNG covered an area of 29.7 Mha while cutover forest comprised 3.4 Mha (PNGFA 2007; Fox et al. 2008). Cutover forests now amount to 10% of forested areas, which is an important part of the forest resource of the country (Fox et al. 2008). However, this portion of the forest resource is generally considered to be degraded, and the timber industry has assumed that it has no current potential for timber production. In the Momase region (Morobe, Madang and Sepik provinces) cutover forest areas comprise approximately 500,000 ha (Fox et al. 2008).

### Challenges and problems

There is an increasing demand for multiple objectives from forest management worldwide. In the context of tropical forest management, these objectives are usually compounded by a wide range of stakeholder expectations and requirements. Because of the complexity of tropical forests, existing approaches to forest management (e.g. modelling and projection) may not be able to meet these demands and changing situations, and new approaches are required. In PNG there are many problems associated with forest management. Apart from stakeholder demands, for example, land and forest ownership issues are complicated.

At present the production capacities of cutover forest areas and secondary forests in PNG are not well understood, and the future of marketing wood products from native forests is also uncertain. While accessible primary forests are being exhausted with the current rate of harvest and the harvesting practice is considered unsustainable, cutover forest areas throughout PNG continue to increase, but with no proper management plans. The capacity of cutover forests to produce timber and other products is not well understood by those involved in forest management. Apart from land and forest ownership problems, there is also a high level of ongoing political interference and corruption in the forestry sector (Jaakko Pöyry 2005; Forest Trends 2006).

## Current issues

### Deforestation

Deforestation in tropical countries has been a major international point of discussion in recent years. As Grainger (1984) points out, deforestation is the temporal or permanent removal of forest cover whether for agricultural or other purposes. The Food and Agriculture Organization of the United Nations (FAO) has estimated the rate of deforestation in the humid tropics to be about 16 Mha/year from studies done in 13 countries including Malaysia and PNG. However, these estimates were doubtful as Lanely's systematic approach (Lanley 1981) in 55 tropical countries put the deforestation rate in the tropics to be 6 Mha/year. According to the FAO's 2005 global forest resources assessment report (FAO 2006), each year about 13 Mha of the world's forests are lost due to deforestation. From 1990 to 2000, net forest loss was 8.9 Mha/year, from which primary forest was lost at a rate of 6 Mha/year through deforestation or selective harvesting. Among the 10 countries with the largest net forest loss per year between 2000 and 2005, Brazil, Indonesia, Myanmar and Zambia were at the top on the list. During the same period, net forest loss was 7.3 Mha/year, which is equivalent to 200 km$^2$/day.

As in many other developing countries in the tropics, PNG's natural forests are being exploited at an overwhelming rate. Estimates show that the country's forest cover declined at a rate of 113,000–120,000 ha/year (PNGFA 2003; FAO 2005) before 2005 through harvesting, agricultural activities, mining and other land uses. Earlier, the 2000 World Bank statistics estimated that, from 1980 to 1990, the deforestation rate in PNG was 0.3% annually (Forestry Compendium 2003), 0.44% between 1990 and 2000, and 0.46% from 2000 to 2005 (FAO 2005, 2007; ITTO 2007). In a recent study by the University of PNG's remote sensing department, the deforestation rate in PNG was estimated to rise from annual rates of 0.4% to 1.4% between 1972 to 2002 (Shearman et al. 2009a, b).

## Illegal harvesting

The worldwide campaign against illegal harvesting in developing countries, especially Africa, Asia and the Pacific, is attracting support from governments of Organisation for Economic Cooperation and Development countries including the United States of America, the United Kingdom and Australia (Curtin 2005). However, there is also an argument that these governments are more concerned with protecting their own timber industries from competition from other producers, especially in the tropical region including countries such as Indonesia and PNG. According to the Australian Department of Agriculture, Fisheries and Forestry, citing a report by Jaakko Pöyry (2005), illegal harvesting is defined as harvesting without authority in national parks or conservation reserves, and avoiding full payment of royalty, taxes or charges. However, it fails to identify any violations of its criteria.

In PNG, the government has commissioned five separate reviews of the administration and operations of the forest-harvesting industry from 2000 to 2005 (Forest Trends 2006). These reviews were conducted in response to concerns raised by the public that the operations of the timber industry were not providing long-term benefits to the country and its peoples, and to assess the implementation of amendments to the Forestry Act 1991 (Ministry of Forests 1991a, b). Of the 14 active harvesting operations investigated under one of the five reviews, it was found that all of these projects were operating illegally, although two projects were found to have better than average compliance with existing laws and regulations. The report by Forest Trends (2006) is contradictory to claims by Curtin (2005) in which he points out that audits of the PNG timber industry sponsored by the World Bank from 2000 to 2004 found full compliance by the industry with the country's Forestry Act 1991.

According to the International Tropical Timber Organization (ITTO) (2006), illegal harvesting is a critical obstacle to sustainable forest management (SFM) in both the production and protection of forest areas in many ITTO producer member countries; however, efforts to combat illegal harvesting and illegal trade through bilateral agreements are emerging. For example, in Indonesia and Malaysia, governments developed a system of government to government timber trade in 2004 whereby only logs received through government-designated ports are considered legal. Multilateral initiatives have also been put in place to combat illegal harvesting, for example the 2001 introduction of Forest Law Enforcement and Governance (ITTO 2006) in East Asia, which resulted in the Bali Ministerial Declaration in which both producer and consumer countries agreed to take actions to suppress illegal harvesting.

## Community forestry

Throughout tropical countries, communities have raised concern that very few benefits have been reaching the owners of land and forests from large-scale commercial harvesting operations. Furthermore, local people value forests not only for timber products but also for other benefits and services; hence, there has been increasing local community-group involvement in small-scale forestry projects. Many of these projects are community-based and involve small-scale sawmilling with the primary aims of producing sawn timber to build homes and selling surplus sawn timbers to generate some income for the community groups to improve livelihoods.

In PNG, non-government organisations (NGOs), community-based organisations and conservation groups have participated in community forestry-related activities. Some of these groups include: the Village Development Trust (VDT), the World Wide Fund for Nature (WWF), the Foundation for People and Community Development (FPCD) and the Madang Forest Resource Owners Association.

In countries such as India, Nepal and the Philippines, community forestry and joint forest-management initiatives have been found to be fairly successful (Mery et al. 2005) in that community forestry-related activities promote the customary management systems that existed before the state assumed control of forest lands. Experiences show that local institutions make better use of forests, manage them more sustainably and contribute more equitably to livelihoods than central government agencies.

## Requirements for certification

Certification of forest management is seen as a requirement in the forestry sector in the tropics (Alder et al. 2002). Forest certification has developed as a way of providing timber consumers with information about the management of forests from which certain timber products have originated. In recent years several certification bodies have been established by interest groups to provide a framework in which certification initiatives can be pursued and managed. The two largest schemes are the Forest Stewardship Council (FSC), which was established in 1993 and is driven largely by environmental NGOs, and the Programme for the Endorsement of Forest Certification, which was established in 1999 with the support of the international forest industry, trade organisations and associations representing woodland owners in Europe. Several regions and countries including Europe, New Zealand and Japan have also developed public procurement policies to promote SFM, good forest governance and sustainable use of


Certified timber stockpiled in preparation for export to Australia, Madang province, Papua New Guinea (Photo: Jim Grigoriou).

forest products by consumers (Freeman 2006). Some tropical countries are also now developing their own certification systems. They include the Malaysian Timber Certification Council, the Ecolabelling Institute in Indonesia and the Certificação Florestal in Brazil. Countries in Africa are also developing a regional initiative. According to ITTO (2007), there has been a lot of progress in certification requirements in ITTO producer countries; however, more than 90% of currently certified forests worldwide are outside the tropics. This scenario indicates the difficulties associated with implementing SFM in the tropics.

In the report by Mery et al. (2005), it was noted that almost 200 Mha of forests had been certified at a global level. It is considered that the process of forest certification is a market-driven approach that focuses on improving forest management by linking consumer concerns about social issues and the environment to good practices. Certification schemes provide consumers alike, including governments, retailers and individuals, with an assurance that they are buying products that come from forests that are sustainably managed in a socially responsible way.

## Certification efforts in PNG

Papua New Guinea has a national FSC working group in place and has developed national certification standards. The extent of FSC-certified forest areas in PNG is one area of 19,215 ha consisting of semi-natural and mixed plantation forests and natural forests. This figure may have been increased in recent years, driven by activity by NGOs and environmental groups under the banner of FSC to certify projects in various parts of the country. The efforts of some NGOs in PNG include the following: Forest Management and Product Certification Service (FORCERT) in West New Britain, WWF in Western province, VDT in Lae and FPCD in Madang. FSC activities in PNG include training and capacity building for local NGO partners.

Community groups in PNG have very little capacity to achieve FSC certification standards, and find that meeting certification requirements is quite difficult and the costs of becoming certified are high. It is a requirement that community groups have to comply with international standards and organise and pay for an independent auditor to assess their forest

Transporting logs to the mill—community forestry on Kwato Island, Milne Bay province (Photo: Julian Fox).

and business operation. To simplify the certification process for community groups, several NGOs (e.g. FORCERT) are managing FSC group certificates. The group certification system works on the basis that individual small-scale producers that meet the set group certificate standards can become group members. The costs of managing the group certificate are shared between the members, who pay an annual fee plus a small levy per cubic metre on all certified timber sold.

Certified timber needs to be able to be followed down the 'marketing chain' from the forest from which it was sourced all the way to the final buyer of the timber product. This 'chain of custody' guarantees buyers of certified products that the timber used came from well-managed forests. Therefore, any trader in certified timber is required to maintain their own chain-of-custody certificate. PNG NGOs (e.g. FORCERT) also manage group chain-of-custody certificates and offer membership to a number of selected, small, central timber yards (central marketing units or CMUs), to which certified producers can sell their timber.

In terms of SFM in PNG, according to ITTO (2006), forest areas designated for management total 5 Mha, of which 1.5 Mha have been considered to be managed sustainably and are expected to undergo certification in the near future.

## Forest governance

According to a report on the state of the world's forests by FAO (2007), the Asia Pacific Forestry Commission (APFC) defines forest governance as the process of making and implementing decisions about forests and forest management at local, national and regional levels. APFC emphasises that frameworks such as forest legislation, regulations, criteria and indicators, and codes of conduct are important in the decision-making process.

In most developing countries, communities living in and around the forest do not have recognised property rights to the forest products that are important to their livelihoods, and their concerns are not considered in forest-policy decision-making processes. National- and local-level governments also lack the necessary authority, capacity and accountability to fulfil their obligations to forest management, and failing governance manifests itself in deforestation in many parts of the tropical region. Over time the scenario has taken a shift as rapid changes relating to expectations and demands on forests by society confront the forestry sector. Those institutions and agencies involved in forest management are now putting into place reforms in order to cope with these changes. In PNG the Forest Authority is now implementing the country's Logging Code of Practice (PNGFA and DEC 1996). Among other controls, the code has a 24-step procedure that has to be met before a licence or permit is granted for any major timber project to start. The PNG Logging Code of Practice has received a lot of support from agencies and stakeholders within the country as well as the international community. The APFC is now implementing a study in the Asia–Pacific region to provide member countries with recommendations about how existing forestry agencies can be restructured or modernised to ensure their continued effectiveness and relevance.

The Special Project on World Forests, Society and Environment of the International Union of Forest Research Organizations in 2005 (Mery et al. 2005) recommended that decentralisation in developing countries should be pursued when the conditions are right. However, in order for this to be effective, the process of decentralisation must be seen to overcome corruption and establish new structures of governance at the local level through participative democracy and self-management. It is considered that these processes may not be easy, especially in developing countries in the tropical region, as multinational corporations with their wealth and monetary power influence government policies to their own advantage in terms of resource development in sectors such as forestry. To support these arguments, it is not surprising that the World Bank Corruption Index (2007) has recently ranked many developing countries in the tropical region among the 20 most corrupt nations in the world, including ranking PNG as number 15.

## Forest management in PNG

The past 20 years has seen forest management in PNG focused mainly on meeting industrial demand for wood products, with little attention given to management for other forest values or meeting local community expectations. Forest management worldwide is in transition from focusing on timber production to being inclusive of non-timber products and other biodiversity values. PNG's forest management objectives need to change to meet both local and international demands, including management for other values such as carbon. While primary forests in

PNG are now being exhausted by commercial harvesting, cutover forest areas and secondary forests may have to be compromised to meet stakeholder demands. The 1991 National Forest Policy does not provide directions on technical aspects of management of cutover forest areas in PNG and there are no guidelines for land-use plans after harvesting. The policy has the following provisions relating to forest management in PNG. Part II, sec. 3 and 4 provide directions on sustained yield management and reforestation, while very limited detail is given in Strategy 11 for community forestry. In Part III, sec. 2, the policy calls for participation of PNG citizens, especially local forest owners in forest industries and enterprises, while Strategy 3 provides guidelines for participation in forest industries by landowner companies and for small national groups to be involved in small-scale processing operations.

In terms of timber harvesting, the annual allowable cut (AAC) for timber concessions in the country is also a policy matter. The policy determines that the AAC be estimated by initially dividing the total merchantable resources within a production forest by an assumed cutting cycle of 35 years. The basis of the cutting cycle for PNG's tropical forests is not clearly known; however, a report by Curtin (2005) in the newsletter of the Commonwealth Forestry Association states that it was the World Bank that imposed the 35-year cycle in both Indonesia and PNG. With changing circumstances and differing objectives relating to forest management in PNG, there is a need to review the current AAC and cutting cycle to reflect the actual extracted timber volume that is produced in each timber concession area.

Generally, a selective-harvesting system is common in many tropical countries. This is the case in PNG where timber harvesting is carried out on the basis of minimum harvesting diameter limits. The cutting limit for the selective-harvesting system in PNG is 50 cm diameter at breast height (dbh). Therefore, in a timber-harvesting operation, all commercial trees with a diameter of 50 cm and above are available for harvest. Because this practice does not take into account different growth rates for different tree species, initial harvesting may be excessive and cause damage to residual stands. The average diameter increment on all commercial timber species has been estimated to be about 0.47–1.0 cm/year (Alder 1998). In terms of clear-felling operations, large extensive natural forests may be clear-felled regardless of the species and different size classes. For example, in the northern part of PNG a timber company has been involved for more than 30 years in clear-felling of extensive natural forest in the Gogol valley in Madang province. The clear-felled areas are often converted into monoculture plantations (one type of species)

Rimbunan Hijau harvesting along a roadside in Madang province outside Forest Management Area boundaries (Photo: Julian Fox).

with species such as *Eucalyptus deglupta*, *Acacia mangium*, *Gmelina arborea* and *Terminalia brassii*.

In the selective-harvesting system used in the region, common diameter limits are 45–50 cm on a cycle of 30–35 years. Table 1 shows the cutting limits and felling cycles in use within the Asian region (Poore et al. 1989).

## Requirements for forest inventory and plans

Forest management and planning are traditionally informed through the use of forest inventory data collected for this purpose from either systematic or random sampling of a given timber concession area of interest. The FAO/DP forest research project on diagnostic sampling (Kingston and Nir 1988); the 1993–99 ITTO forest research project on growth and yield (Alder 1998); and the Australian Centre for International Agricultural Research (ACIAR) Project FST/1998/118 (Keenan et al. 2005) provided some relevant information that may be used also for forest management and planning purposes; however, many of the outputs from these studies have not been considered for forest management and planning in PNG.

Requirements for forest inventory and management plans are mandatory in accordance with the Forest Policy. Development of the forest resource in PNG is often undertaken in compliance with the National Forest Plan, Provincial Forest Plans and National Development Forestry Guidelines. Other supportive documents that provide guidance to ensure compliance and effective monitoring include the Environmental Key Standards, Logging Code of Practice, Forest Management Agreement and Project Agreement (PNGFA and DEC 1996; PNGFA 1996b). The planning of operations in all major timber concession areas is processed and operated in accordance with the national and respective provincial forest plans.

A past review of planning and inventory capacity and requirements in PNG (Keenan et al. 2005) showed that, although it is a requirement under the Forest Policy that all agreements and permits are to be conditional upon broad land-use plans, there is currently no comprehensive land-use planning process in place in PNG. At present there is no general infrastructure plan within which access for timber harvesting can be considered. That review also found that, generally, the PNGFA has very little capacity to achieve the requirement for a 1% inventory for strategic planning because of financial limitations. More so, the inventory requirements for tactical and operational planning are also too demanding and the industry operator often decides what is required for operational purposes.

The details of forest planning and inventory requirements in PNG include the seven levels of planning adopted by PNGFA (Table 2).

## Timber production and trade

In 2003 PNG produced an estimated 7.2 Mm$^3$ of roundwood, of which about 76% (5.5 Mm$^3$) was fuel wood for domestic use (FAO 2005). Total industrial tropical log production was an estimated 2.30 Mm$^3$ in 2003, which is an increase from 2.10 Mm$^3$ in 1999 (ITTO 2004, 2005).

**Table 1.** Cutting limits and felling cycles in the Asian region

| Country | Silvicultural system | Cutting cycle (years) | Diameter limit (cm) |
|---|---|---|---|
| Malaysia: | | | |
| Peninsular | Uniform | 55–60 | 45 |
| | Selection | 30 | 50 for dipterocarps |
| Sabah | Uniform | 60 | 45 for non-dipterocarps |
| | Selection | 35 | 58 |
| Sarawak | Selection | 25 | 50 |
| | | | 48 |
| Philippines | Selection | 30–45 | Retain:<br>70% of 15–65-cm class<br>40% of 65–75-cm class |
| Papua New Guinea | Selection | 35 | 50 |
| Indonesia | Selection | 35 | 50<br>but 60 for jelutong<br>65 for *Agathis* |

**Table 2.** Forest planning and inventory requirements in Papua New Guinea

| Planning level | Inventory planning / Requirement | Standard / Specification | Responsibility | Comment |
|---|---|---|---|---|
| National Forest Plan | Forestry Act s. 47(1) | 1% sample process with FIPS, FIMS and PNGRIS[a] | PNGFA[b] | |
| National Forest Inventory | Forestry Act s. 47(2) | 1% sample, same as above | PNGFA | Significant inventory work done but not a comprehensive National Forest Inventory |
| Provincial Forest Plans | Forestry Act s. 47(2) | 1% sample, same as above, compiled for each province | Provincial Forest Officers | |
| Forest Management Agreement Project Statement (feasibility study / tender) | Forestry Act s. 100 | 1% sample from company plots, different from above | PNGFA | Significant inventory done 1% inventory not necessary for sound statistics |
| 5-year working plan | Forestry Act s. 101 with detailed prescription in the Planning Monitoring and Control Procedures (PMCP) | 1% sample. PMCP states: 'estimate of net harvestable volume must be based at a minimum of a 1% sample of the gross loggable area. Details of net harvestable volumes presented must be based on actual inventory of the areas to be harvested, and not on historical data from previously harvested areas'. | Company | As above |
| Annual logging plan | Forestry Act s. 102 and PMCP | 1% | Company | As above |
| Operational set-up plan (harvesting plan) | PMCP | At minimum, consist of 10% sample of the loggable area | Company | Companies prefer a 20% sample of trees selected to be harvested; some companies assess 100% of trees planned for harvest |

[a] FIPS = Forest Inventory Projection System; FIMS = Forest Inventory Mapping System; PNGRIS = Papua New Guinea Resource Information System
[b] PNGFA= Papua New Guinea Forest Authority
Source: Keenan et al. (2005)

ACIAR projects FST/1998/118 and FST/2004/061 have promoted the use of variable-radius plots for forest assessment (see Brack 2011; Fox et al. 2011). Here, participants at a workshop in Lae are introduced to the prism wedge, which is used in the variable-radius plot method (Photo: Julian Fox).

The forest industry in PNG is predominantly based on log exports. As such, an estimated 2.02 $Mm^3$ tropical logs were exported in 2003, an increase from 1.98 $Mm^3$ in 1999 (ITTO 2004; ITTO 2005), which made PNG the world's second largest exporter of tropical logs after Malaysia. PNG earned US$126m in 2003 from exports of tropical timber, $US109m of which were from logs (ITTO 2005). The principal export market for PNG logs in 2003 was China (62% of all log exports).

According to PNGFA statistics, the estimated area harvested commercially from 1988 to 2007 is over 2 Mha and the timber volume harvested in the form of logs during the same period is over 39 $Mm^3$ (PNGFA 2007). The forestry sector has contributed 177.3m kina (K)/year, on average, in the form of foreign exchange.

## Forest research in PNG

Research in natural forests in PNG began at Kerevat on the Gazelle Peninsula of New Britain in 1953 (Lamb 1990) to develop a monocyclic system of silviculture similar to the Malayan Uniform System, where regeneration and subsequent growth of seedlings are encouraged after harvesting by removing the remaining non-commercial species in the overstorey. By 1965, about 1,000 ha had been treated in this way and a further 400 ha were being treated each year. Since the 1980s, limited research has been carried out in natural forests on an ad hoc basis, especially by international organisations, up to 1989, when the Papua New Guinea Forest Research Institute (PNGFRI) was established. The establishment of the institute resulted from the amalgamation of the former Forest Products, Forest Botany and Forest Management research branches of the Department of Forests. Earlier research work placed emphasis on plantation forestry until the mid 1980s, when it was realised that the future of production forestry in PNG centred on natural forests. Essential resources were diverted towards natural forest management research, with field trials initiated in Bulolo, Madang and Oomsis near Lae.

Due to the fact that most global wood production comes from natural or semi-natural forests rather than plantations, natural forests research and management elsewhere and in PNG remains an important basis to assist sustainable forest management.

PNGFRI aims to provide scientific and technical advice on various management aspects of PNG's tropical forests. Important issues to be researched include: technical information on cutting cycles, harvesting limits, silviculture treatment applications, and many others such as pests, diseases, and soil and water quality. One of the larger research programs being administered by FRI since 1992 is the establishment, measurement and monitoring of an extensive permanent sample plot (PSP) network covering almost all timber concession areas in PNG. This project has had continuous funding support from international organisations such as ITTO and ACIAR, and is still progressing.

## Discussion

Forest management in PNG has focused mainly on large-scale conventional harvesting over the past 20 years to increase revenue to meet national development goals, with less attention given to community-level forest management. Natural forests are being exhausted in PNG through commercial timber harvesting and other land uses such as large-scale forest conversion to agriculture and shifting cultivation. Therefore, forest management will begin to focus on cutover secondary forests, and a new paradigm in forest use and management is likely to emerge as cutover forest areas are taken over by community landowner groups. Given customary ownership arrangements, the future management of cutover forests is likely to be decided by local community groups.

A concerning development is the PNG Government's rapid expansion of Special Agricultural and Business Leases (SABLs). SABLs may limit landowner rights and their access to traditional lands and forests. In SABLs, forest lands that may be originally intended for agricultural development, usually for a lease period of 99 years, could be diverted to other land uses (especially large-scale harvesting) by foreign or multinational corporations without proper landowner consent.

Forest policy in PNG is administered by the PNGFA under the provisions of the Forestry Act 1991. The policy calls for skills and technology transfer, and the export of value-added products. However, until now little progress has been made in terms of phasing out log exports and increasing domestic processing despite many previous attempts. In 2008 the National Minister for Forests announced the phase-out of log exports from PNG by 2010 in favour of increased downstream processing of wood products (ITTO 2008). There is no evidence that this has occurred.

There were four main driving forces of the major Forest Policy change in 1991. These were: to remove

PNG Forest Research Institute (FRI) located in Lae, Papua New Guinea. Pictured are ACIAR FST/2004/061 project staff; left to right: Francis Inude (Village Development Trust), Kunsey Lavong (FRI) and Joe Pokana (formerly FRI now PNG Office of Climate Change and Development) (Photo: Julian Fox).

the shortcomings of the previous policy of 1987; to address the recommendations of the Barnett Forest Industry Inquiry of 1989 and the World Bank Review of 1990; and to adjust to new situations in the forestry and forest industry sectors (Ministry of Forests 1991a). Since then, new problems and challenges associated with forest management in PNG have emerged. For example, community expectations and demands have increased in forest management, and these have put additional pressure on the PNGFA. The PNGFA has had budgetary limitations and these have affected full implementation of policy and other government requirements. The budget shortfall has also limited the inventory of major Forest Management Areas (FMAs) over the past 10 years. While the industry has increased harvesting of accessible primary forest areas, little attention has been given to management of cutover forest areas, many of which have been left to degrade over time.

## Conclusions

This review of the stages of development of forest management, and the current state of forest resources in PNG, is drawn from published material consulted by the authors. The review considers that, after over two decades of commercial harvesting of primary forests in PNG, there are still no land-use plans for the management of forest areas left behind after harvesting. A major challenge for the PNGFA and the government is the development of appropriate managements systems for cutover forests. Management planning should include consideration of the future production capacity of cutover and degraded forests and the development of the capacity of local forest-owner communities to participate in small-scale forest management and utilisation, for example through management systems that are compliant with requirements of certification bodies.

A new direction in forest policy is now necessary to meet the increasing demands and expectations of stakeholders in PNG as well as the international community. There is a need for policy change to reflect new circumstances in forest management. Policy must be changed to meet the need for an integrated and participatory approach to the management of forests that have been overexploited. Capacity building is required at the community level to address the needs of forest owners and other stakeholder expectations and the demands for small-scale forest management and utilisation.

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# Forest carbon and REDD+ in Papua New Guinea

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*Abstract*

REDD+ (reducing emissions from deforestation and forest degradation and enhancement of forest carbon stocks) is a climate-change mitigation initiative that can potentially offer economic, environmental and social benefits to developing tropical nations with the intersection of carbon markets, climate and environmental protection. If implemented appropriately, it could also provide wider social and economic opportunities for the people of Papua New Guinea (PNG). This paper will trace the development of REDD+ and the emergence of methodology for measurement, reporting and verifying (MRV) greenhouse gas emissions from land use, land-use change and forestry. Past experiences in PNG will be described along with future directions.

Papua New Guinea has been an international proponent of REDD+ with strong endorsement from the Prime Minister Sir Michael Somare. Unfortunately, in-country implementation has been problematic. The stakes for PNG are high—80% of the population is directly dependent on forest environments for their subsistence and livelihood, with Human Development Indexes well below world standards; and almost all of PNG's anthropogenic emissions are from deforestation and forest degradation. Work on forest carbon stock assessment that can contribute to MRV systems will be described. A sound and defensible MRV system is required to report emissions reductions due to changed land-use and forestry practices that are targeted in REDD+.

## Introduction

### Background to REDD and REDD+

Forests play an integral part in stabilising rising atmospheric carbon dioxide ($CO_2$) concentrations through the absorption of $CO_2$ and the sequestration of carbon (C) in living tree biomass. In particular, tropical forests have been recognised for their ability to absorb and store C in forest biomass. Such forests are characteristic of those found in equatorial regions such as in PNG. This has been acknowledged in international climate-change negotiations; and at the Montreal Conference of the Parties (COP 11) in 2005, PNG and Costa Rica requested a new COP agenda item on reducing emissions from deforestation in developing countries (REDD). Subsequently, a 2-year process was launched to develop the new agenda item, which changed to include degradation, with REDD becoming 'reducing emissions from deforestation and forest degradation'.

At COP 13 in Bali in 2007, delegates recommended that efforts to reduce emissions from deforestation and forest degradation should be 'strengthened and supported', but stopped short of calling for anything other than voluntary action on REDD. However, there was a consensus that the REDD initiative should move forward; consequently, industrialised governments pledged US$165m toward the World Bank's newly created Forest Carbon Partnership Facility, a scheme that will offer tropical countries payments to reduce emissions from deforestation and other aspects of the REDD agenda.

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Another 2-year process to develop REDD methodology was launched.

Prior to COP 15 in Copenhagen in 2009, a detailed REDD draft text was prepared by technical working groups. Delegates at COP 15 agreed to adopt elements of the draft text. In particular, REDD+ methodology emerged—methodological guidance for activities relating to reducing emissions from deforestation and forest degradation, as well as the role of conservation, sustainable management of forests and enhancement of forest C stocks, in developing countries. An important element of methodological guidance from COP 15 was on measurement, reporting and verification (MRV) of emissions (e.g. establishing reference emissions levels and national monitoring systems; use of Intergovernmental Panel on Climate Change (IPCC) guidelines (IPCC 2003, 2006) and reporting variables).

In Cancun at COP 16 in 2010, REDD+ gained further momentum—delegates encouraged developing-country parties to contribute to mitigation actions in the forest sector by undertaking the following activities, as deemed appropriate by each party and in accordance with their respective capabilities and national circumstances: reducing emissions from deforestation; reducing emissions from forest degradation; conservation of forest C stocks; sustainable management of forest; enhancement of forest C stocks (UNFCCC 2010). Further guidance on REDD+ readiness and methodology was also provided, stating that a phased approach will likely be necessary—from plans and implementation (phase 1 and 2) to results-based activities (phase 3)—and listing the systems and information that developing countries will need to undertake REDD+ activities. These include a national plan, a national reference emissions level, and a robust and transparent national forest monitoring system. The agreement represented a step towards a fully fledged REDD+ framework.

## Carbon markets and forestry projects

Carbon markets consist of compliance and voluntary markets. Compliance markets are regulated by national or international C emissions reduction regimes, for example the Kyoto Protocol reporting to the United Nations Framework Convention on Climate Change (UNFCCC), the European Union's Emissions Trading Scheme, or the New Zealand Emissions Trading Scheme.

Voluntary C markets function outside the compliance markets and enable companies and individuals to purchase C offsets on a voluntary basis. Carbon has been traded on voluntary markets since the 1980s. By paying someone else to reduce greenhouse gas (GHG) emissions elsewhere, the purchaser of a C offset aims to compensate for—or 'offset'—their own emissions. For example, individuals can seek to offset their travel emissions, and companies can claim 'climate neutrality' by buying large quantities of offsets to 'neutralise' their C footprint or that of their products.

Voluntary C markets are not under government regulation, and have sometimes been criticised for poor project design and poor C accounting systems. To address these concerns, voluntary offset standards, such as the Voluntary Carbon Standard (VCS 2008a, b, c), have been created to ensure that acceptable methodology and accounting systems are used.

In the forestry context, voluntary C markets provide a useful project-based mechanism for reducing emissions, which can be measured and verified against the VCS or another standard (Kollmuss et al. 2008) and can be traded in these markets. Forestry projects account for 24% of voluntary C projects—afforestation/reforestation (10%), reduced emissions from deforestation and degradation (7%) and improved forest management (3%) (Hamilton et al. 2010). There has been a recent drop in the volume of C traded on global voluntary C markets (Hamilton et al. 2010).

VCS (and other standards) have provided useful project-based methodology; voluntary C projects are operating for all activities that may be included in national reporting for REDD+.

## Monitoring, reporting and verification for REDD+

Important methodological guidance on MRV has emerged from the Copenhagen and Cancun texts. They have indicated that MRV systems for REDD+ should be based on IPCC Guidelines for Annex 1 countries GHG reporting under the Kyoto Protocol at one of the three tiers identified in the guidelines for the accuracy of reporting (IPCC 2006).

MRV systems will need to account for all C pools affected by land use, land-use change and forestry (LULUCF), and should be spatially explicit. Therefore, a combination of ground-based C pool assessment and remote sensing should be used, similar to almost all national GHG reporting mechanisms for the Kyoto Protocol.

## PNG background

Forests play a vital role in sustaining the traditional subsistence livelihoods of most of PNG's indigenous population. Forest resources are also a major contributor to the national economy—the sector employs about 10,000 people, log exports were valued at over US$170m in 2006, and these exports contributed some K200m (kina) in export duties, royalties and taxes (PNGFA 2009).

However, forest-harvesting operations often do not meet required standards or deliver long-term benefits for landowners (Laurance et al. 2011). Basic health and education services are lacking in many areas of PNG, which is ranked 149th of 177 countries in the UN's Human Development Index. With a high level of forest exploitation but poor returns to resource owners, it is little wonder that REDD+ has generated much interest as a potential alternative income source within PNG. Furthermore, selective harvesting and land-use change due to agriculture are responsible for a majority of PNG's anthropogenic emissions (Hunt 2011). However, significant policy, institutional and technical challenges need to be overcome before REDD+ becomes operational (Howes 2009; Melick 2010).

### Voluntary carbon in PNG

PNG has a history of 'cargo cults' and voluntary C agreements have become a new version of the phenomenon in PNG in recent years. A number of intermediary brokers entered into agreements with forest-owning communities for voluntary C agreements that became known as 'mani bilong skai'—sky money, because they appeared to be trading air. Local confidence tricksters as well as prospective C traders from Australia took advantage of the situation, signing up local communities to bogus trading deals. The agreements were unlawful and, as of late 2010, the PNG Government has put a moratorium on forestry voluntary C projects until further notice.

### A rocky road to REDD+

Prime Minister Sir Michael Somare has strongly endorsed PNG's participation in REDD. Internationally, PNG has been at the forefront of negotiations on REDD+, mainly through the partnership of Coalition for Rainforest Nations. However, domestically, REDD+ implementation has been problematic. The Office of Climate Change and Environmental Sustainability (OCCES) was


Large-scale harvesting offers temporary employment for communities, but monetary returns to the community and ongoing benefits can be limited. (Photo: Joe Pokana). See Hunt (2010, 2011).

established in 2008 to oversee domestic REDD+ implementation. Unfortunately, it has been plagued by corruption. Unauthorised carbon credit certificates for large areas of PNG were issued by OCCES and signed by former Director, Dr Theo Yasause. Following numerous allegations that OCCES accepted money from C trading companies for credit certificates, Theo Yasause was suspended, and OCCES was dissolved, with many staff dismissed during 2010. This was a less than ideal start to PNG's participation in REDD.

## ACIAR project FST/2004/061

ACIAR project FST/2004/061 had the objective of analysing the potential of PNG forests to supply different types of services to local communities while developing tools to improve forest management. Working closely with staff from the PNG Forest Research Institute (PNGFRI) and the Village Development Trust, the project developed tools that can inform village-level and government decision-making. Forest assessment tools, which are based on forest modelling, remote sensing, field assessment and geographic information systems, provide information on C, timber and biodiversity to local communities and forest-management agencies. Ultimately, these tools and the improved information they provide can facilitate improved decision-making.

While the project was mainly concerned with improved timber assessment and developing systems for community forest management, during the term of the project (2008–10) there was intense interest both from within PNG and among the international scientific community to develop methodology to support the REDD+ mechanism.

Technical challenges facing REDD+ implementation include: estimation of forest C stock in different forest strata (Gibbs et al. 2007); change in these stocks due to forest harvesting (Kauffman et al. 2009) and forest fires (Phillips et al. 2004); and estimating rates of C sequestration in primary and regenerating forests across the forest estate (Olander et al. 2008). The forest-assessment work undertaken as part of ACIAR project FST/2004/061 provided an opportunity for linking ground-based and remote sensing data for estimation of forest C from permanent sample plots (PSPs) and the estimation of C flux due to selective harvesting and fires.

### Permanent sample plots in PNG

Papua New Guinea has a comprehensive PSP network maintained by the PNGFRI that has been remeasured and maintained with previous support from ACIAR. Project FST/2004/061 undertook significant work to improve the database, remove persistent errors and make it accessible for analysis. Targeted remeasurement of PSPs and the collection of ancillary information such as spatial location and soil C samples added valuable information. The PSPs provided an opportunity to analyse the C balance of PNG's forests over a measurement period of 15 years (Fox et al. 2010) as well as the recovery trends in harvested forest (Yosi et al. 2011).

### Forest C stock estimates for PNG

Analysis of PSPs provided the first comprehensive assessment of above-ground C stocks for native forests in PNG, along with methods that can be used for estimating forest C from other forest inventory data (Fox et al. 2010). Average above-ground C in stems greater than 10 cm diameter for 115 selectively harvested 1-ha plots in lowland tropical forest was 66.3 ± 3.5 tC/ha (95% confidence interval (CI)), while for 10 primary forest plots the average was 106.3 ± 16.2 tC/ha. We applied ratios based on field observation, in-country studies and the literature to estimate unmeasured pools of above-ground C (stems less than 10 cm diameter, fine litter and coarse woody debris). Total above-ground C was estimated as 90.2 and 120.8 tC/ha in selectively harvested and primary lowland forest, respectively. The estimate for primary tropical forest was lower than biome averages for tropical equatorial forest, and we hypothesised that disturbances such as fire, landslides and traditional shifting agriculture (in some regions) was limiting C stock development. Outputs from this work have encouraged transparency and consistency in the estimation of forest C within PNG (Fox et al. 2010).

The PSP system and forest C stock assessment also provide a basis for PNG's national forest carbon inventory, which should commence during 2011 as part of MRV activities. New plots established as part of the MRV methodology should use the PSP database and field measurement protocols so that future measurements are consistent with historical measurements. There is a need to extend the coverage of these plots, with a wider sample in primary forest that can be matched to the areas impacted by harvesting (Bryan et al. 2011). Additional forest

An isolated village (Aramore) deep in the forests of Madang province has no health or education services (Photo: Julian Fox).

Effectively communicating issues associated with climate change and REDD+ in Papua New Guinea must start in the village. Here, Francis Inude (Village Development Trust) explains to the Kgwan community of Simbu province the basis for REDD+ and the need to establish a permanent sample plot to monitor forest growth on their tribal lands (Photo: Joe Pokana).

C pools should also be sampled, for example below-ground live biomass, above-ground live biomass (AGLB) in trees with diameter at breast height over bark less than 10 cm, and coarse woody debris.

### C stock change due to selective harvesting

Fox et al. (2010) presented a methodology for estimating forest C from PSPs. However, it is the change in forest C pools over space and time and consequent emissions of $CO_2$ to, or removals from (uptake of C in living biomass), the atmosphere due to different land-use activities that are most important for REDD+ implementation (Gibbs et al. 2007). There is also considerable scientific debate regarding rates of C sequestration in primary (undisturbed) and secondary (disturbed, e.g. harvested) tropical forests (Clark et al. 2001; Wright 2005). Many questions remain: for example, 'How much forest C is removed during selective harvesting?'; 'Does the C recover, and how long is it to recovery?' These questions need to be answered to quantify the C dynamic associated with selective harvesting in PNG—the most important anthropogenic LULUCF component of an MRV methodology in PNG.

To examine this, the PSPs were used to assess the impact of selective harvesting and the El Niño – Southern Oscillation (ENSO)-induced fires on forest C and sequestration (Fox et al. 2011). To achieve this, a hierarchical Bayesian model (HBM) was developed and parameters derived that can be used to estimate the C and $CO_2$ balance of selective harvesting, forest regeneration and degradation after fire. A linear HBM of C sequestration against time was fitted separately to data for the three strata represented in the PSP database—primary, selectively harvested and ENSO-burnt forest. It was assumed that $t_0$ was the date of first measurement for primary plots; the harvesting date for selectively harvested plots; and the date of the ENSO fire (1998) for burnt plots.

HBM parameters indicated: C stock in AGLB of 137 ± 9 tC/ha(95% CI) in primary forest, compared with 62 ± 18 tC/ha for selectively harvested forest (55% difference); a C sequestration rate in primary forest of 0.23 ± 1.70 tC/ha/year, which was lower than in selectively harvested forest at 1.12 ± 3.41 tC/ha/year; and ENSO-induced fire resulting in significant C emissions (–6.87 ± 3.94 tC/ha/year). High variability between PSPs in C stock and C sequestration rates, and

ACIAR projects often involve collaborative scientific work and capacity building of partner organisations. These participants from government, universities, non-government organisations and communities in Papua New Guinea participated in the workshop 'Improving inventory for timber and carbon in Papua New Guinea', held at the PNG Forest Research Institute, Lae, during April 2009.

autocorrelation among remeasurements of individual PSPs, necessitated the use of random plot effects for both stock and sequestration.

The HBM approach allowed inclusion of hierarchical autocorrelation, providing valid confidence intervals on model parameters and efficient estimation. The most important outcome was that selective harvesting resulted in a change in AGLB of 75 tC/ha (a 55% reduction). This result is relevant to MRV calculations as it allows an estimate of the $CO_2$ emissions associated with selective harvesting in PNG.

### The C balance of selective harvesting in PNG

Selective harvesting alters the C and $CO_2$ balance of forest ecosystems—sequestration, respiration and combustion are all enhanced. Selective harvesting in the tropics results in increased residue and enhanced levels of $CO_2$ respiration as residue decays. If regrowth is successful, increased C sequestration in regrowing forest can result. Harvesting also results in increased combustion associated with fuel consumption releasing $CO_2$. In addition, $CO_2$ is stored in wood products. Basically, a C accounting exercise is required to account for the change in each pool on a temporal basis. This was done for PNG based on all available information in Fox and Keenan (2011).

Building on the work of Fox and Keenan (2011), Coote and Fox (2011) developed scenario analysis capability for modelling $CO_2$ emissions in PNG. The approach taken is to compare a $CO_2$ emissions abatement scenario due to changed forest management against a business-as-usual baseline based on current practices for the period 2008–28. The model was used to produce $CO_2$ emissions abatement estimates for four simple scenarios: ceasing log export post 2011 and adding 250,000 $m^3$/year to local processing volumes (up to 1.5 million $m^3$/year); reducing collateral damage in above- and below-ground biomass by 32% using reduced-impact harvesting methods; increasing regeneration success on selectively harvested areas from 75% to 100%; and increasing harvested volume utilisation from 33% to 66%.

The permanent sample plot (PSP) system in Papua New Guinea provides an important basis for future forest carbon inventory undertaken as part of measurement, reporting and verification activities. Here PSP team member Silver Masbong (right) and local assistant Michael (left) establish the first PSP in high-elevation forests of Simbu province (Photo: Joe Pokana).

## PNG—the way forward

A new office has been created to oversee REDD+ implementation—the PNG Office of Climate Change and Development (OCCD). The OCCD is much smaller than the original, and it is envisaged that work related to REDD+ will be shared among relevant PNG government departments such as the Forest Authority, FRI and the Department of Environment and Conservation. The OCCD is guiding PNG through Phase 1 of REDD+ preparedness: the development of national strategies, policies, measures and capacity building. One of the first tasks is to design an MRV system for measuring emissions from LULUCF.

It is envisaged that the MRV responsibilities will be jointly overseen and undertaken by the government departments mentioned above. Improved coordination is required if MRV activities are going to progress in PNG, with agreement on tasks, assigned roles and implementation timetables. The challenges of building effective across-government collaboration and the complexity of dealing with the millions of forest landowners in PNG means that REDD+ implementation is likely to be a long-term process. It could take 5–10 years before an effective national MRV system for REDD+ reporting is in place, and even longer before benefit-sharing and forest-management agreements are developed with local landowners.

We have briefly demonstrated technical work that can assist REDD+ and MRV implementation in PNG. However, much institutional capacity building is required before MRV systems can be designed and operated in country. While many people consider that credits from REDD+ can provide a rapid and low-cost climate-mitigation option, we agree with Howes (2009) that this will neither be cheap nor easy in PNG.

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Trained community members will be an integral part of efforts to monitor forest carbon stock in their tribal lands. Here, young community members from the Sob tribe of Madang measure tree height using a clinometer (Photo: Julian Fox).

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# Assessment

# Assessment of timber and carbon stocks for community forest management

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*Abstract*

A cost-effective methodology for assessment of timber and carbon stocks is described based on field-data collection integrated with remote sensing. Field-data collection used stratified random point sampling with a basal area factor 2 prism wedge. The ISODATA classification algorithm was applied to cloud-free advanced spaceborne thermal emission and reflection radiometer (ASTER) optical data to classify land cover for the Sogi project area. ASTER data were also used to derive a digital elevation model, which is useful for planning, particularly in steep and difficult terrain such as encountered in Papua New Guinea. Land-cover classifications were primary forest, secondary (disturbed) forest, gardens and villages. Field sampling intensity met an accuracy requirement of being 90% confident of being within 10% of the true mean for the two forest strata—primary and secondary forest. Point estimates of above-ground carbon and merchantable timber volume were correlated against ASTER spectral bands, and spatial predictive models were derived for generating maps of forest carbon in above-ground live biomass and timber resources. Maps of forest resources were provided to communities, and it is hoped that this information can improve community decision-making. Explicitly, options for forest utilisation such as commercial harvesting for whole-log export or certified community forestry can be compared with alternative revenue sources such as from voluntary carbon agreements. A simple spreadsheet was designed for data entry, with inbuilt allometrics for calculation of timber and carbon stocks.

## Introduction

Modern forest inventory techniques such as variable-radius sampling (also known as point samples or plotless samples) were proposed for general use in Papua New Guinea (PNG) by Australian Centre for International Agricultural Research (ACIAR) project FST/1998/118, ‘Planning methods for sustainable management of timber stocks in Papua New Guinea’. Techniques such as variable-radius sampling are more efficient for estimating volume, biomass or value in a forest compared with plot-based inventories. For community forest assessment we build on this and develop a stratified random variable-radius plot-sampling strategy to estimate forest stocking, composition, merchantable timber volume and forest carbon (C). This modern forest-inventory approach also facilitates calibration of remotely sensed estimates of merchantable volume and biomass for wall-to-wall mapping.

The forest classification and assessment technique developed here can be used more generally to improve the efficiency and accuracy of forest assessment in PNG. Current inventory methods prescribed in the PNG Forestry Act 1991 require a stripline sampling approach covering 1% of the forest area, and this approach is used by both the Papua New Guinea Forest Authority (PNGFA) and forest certification bodies. The approach is inefficient and may be biased, as the forest sampled on striplines may not be representative of other areas of the resource.

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There is considerable scope to improve the accuracy and efficiency of the stripline approach using some of the techniques described here (see also Brack 2011).

The objective of the remote-sensing component of ACIAR project FST/2004/061 was to develop a cost-effective system that could be applied for forest assessment in PNG to support community forest management. Many remote-sensing data sources are prohibitively expensive in either image acquisition or processing. The application of optical remote sensing in the tropics is restricted by the prevalence of clouds, which preclude ground reflection. Optical sensors with low temporal resolution (infrequent acquisition over the area of interest) will be restricted due to difficulties in acquiring cloud-free images. Other remote-sensing data sources such as synthetic aperture radar are unaffected by cloud cover but require complicated processing that is computationally intensive.

A review of cost-effective methods for tropical forest assessment identified the ASTER platform as suitable for PNG. ASTER has been successfully used to estimate and map above-ground forest C (Iwashita et al. 2006; Buhe et al. 2007; Muukkonen and Heiskanen 2007; Fuchs et al. 2009). ASTER has also been used to derive digital elevation models (DEMs) (Feldpausch et al. 2006). Most importantly, it has successfully been used to differentiate primary and selectively harvested forest in the tropics (e.g. Broadbent et al. 2006), which is a requirement for assessment of forests in PNG due to the extensive and expanding areas that have been selectively harvested (Filer et al. 2009; Shearman et al. 2009). ASTER data has also shown potential for forest-change detection (Wulder et al. 2008).

# Methods

The basic methodology for community forest assessment is:

1. Stratify the forest resource using ASTER remote sensing.
2. Conduct a pilot sample of the stratified resource by placing 20 random variable-radius plots in each stratum.
3. Use sampling statistics to determine the number of further plots to satisfy accuracy limits.
4. Finalise field sampling.
5. Use spatial modelling of above-ground live biomass (AGLB) and merchantable volume from field samples against spectral information from ASTER data.
6. Predict wall-to-wall geographic information system (GIS) layers.
7. Create maps and summary information for communities.

## Study areas

In consultation with project partner Village Development Trust (VDT) for ACIAR project FST/2004/061, areas for assessment work were identified as: the medium-scale community operations of Sogi (13,000 ha) in Madang province and Kgwan in Simbu province (20,000 ha), and the small-scale operations at Yalu (5,000 ha) and Gabensis (2,000 ha) in Morobe province. Sogi and Kgwan community operations are based in primary forest, while Yalu and Gabensis are based in secondary forest. The Sogi project area was used to develop the methodology for forest assessment, and results for Sogi will be solely described in this paper.

The Sogi medium-scale ecoforestry project was initiated and is maintained by VDT and is so named because it incorporates two language groups—the Sob and the Girawa. It is located close to Madang and extends over a large area of primary rainforest with a population of 2,600 living in eight distinct villages. Figure 1 is a satellite image of the Sogi project area showing the locations of the eight villages.

## Remote sensing

To facilitate forest classification in community areas, a suite of remotely sensed optical (LANDSAT 5, LANDSAT 7 ETM and ASTER) and radar (JERS-1) data were acquired for the study areas. Geo-corrected radar data from the JERS-1 platform were acquired for the entire land area of PNG and were processed to provide forest canopy backscatter information. To complement optical and radar data, bioclimatic data have also been acquired for PNG from the WorldClim database (Hijmans et al. 2005); these data have been found to complement remotely sensed data for the modelling of forest biomass. Unfortunately, forest classification using JERS-1 and LANDSAT was limited by poor resolution and persistent cloud cover, respectively, and these approaches were discontinued in favour of ASTER, which was found to be useful for forest classification and modelling for the study areas. ASTER data were also processed to create DEMs that described the hilly topography of project areas. DEMs are useful for forest planning and for informing the best route for road construction, particularly in the Sogi and Kgwan project areas.

Professor Rod Keenan discussing ACIAR project FST/2004/061 with the Sogi community (Photo: Julian Fox).


**Figure 1.** Location of the Sogi project area

## ASTER data

ASTER is mounted on the EOS-AM1 platform, launched on 18 December 1999. The ASTER instrument covers a wide spectral range, with 14 bands from the visible to the thermal infrared, and high spatial, spectral and radiometric resolution. An addition, a backward-looking near-infrared band provides stereo coverage that is useful for generating DEMs. The visible and near-infrared (VNIR) has three bands covering the wavelength range 0.52–0.86 µm (green, red, near-infrared), with a spatial resolution of 15 m; the short-wave infrared (SWIR) has six bands in the range 1.6–2.4 µm, with a spatial resolution of 30 m; and the thermal infrared (TIR) has five bands in the range 8.1–11.3 µm, with a ground resolution of 90 m.

A cloud-free Aster Level 1B with date of acquisition 24/07/2004 and Granule ID ASTL1B 0407240042370806041015 was downloaded from the Japanese Space Agency website (http://imsweb.aster.ersdac.or.jp/ims/html/DPR/DPR_Menu.html).

Raw ASTER data were read into ENVI software, and 16 bands were output as WGS 1984 UTM Zone 55 projected layers that could be read by ArcGIS. Three VNIR (15-m) and six SWIR (30-m) bands were generalised to 30-m resolution GeoTIFFS, which were read into ArcGIS for classification and integration with field data. Bands were numbered 1–9 in order of increasing wavelength. TIR (90-m) bands were not used in this analysis.

### Classification and stratification

Unsupervised classification is a common preliminary remote-sensing task when little a priori information is available; it is important as it can guide stratification and therefore improve the precision of sampling designs. The ISODATA unsupervised classification algorithm (Memarsadeghi 2007) is computationally efficient and has proven effective for classifying land cover from Landsat data. It should work well with ASTER, as spectral bands are analogous to those derived from Landsat (Iwashita et al. 2006), and this has been demonstrated for tropical forest by Souza et al. (2003).

ISODATA unsupervised classification calculates class means evenly distributed in the data space, then iteratively clusters the remaining pixels using minimum distance techniques. Each iteration recalculates means and reclassifies pixels with respect to the new means. This process continues until either the number of pixels in each class changes by less than the selected pixel change threshold or the maximum number of iterations is reached. The ISODATA algorithm in ENVI was applied to ASTER bands 1–10. ISODATA resulted in eight classes (0–7), which corresponded to bare ground for the first category (0) and increasing forest density for the other seven classes. This was confirmed based on limited sampling of bare-ground gardens and primary and secondary forest around Yagi village undertaken during 2008, where class 1 was designated bare ground, classes 2–3 secondary forest and classes 4–7 primary forest. This preliminary classification was used to stratify the Sogi forest to improve the precision of field measurements. Preliminary maps were created identifying primary and secondary forest, as shown in Figure 2.

### Field sampling design

Field sampling design comprised the following methodology:

1. After stratification based on ASTER remote sensing, a pilot survey of each stratum was undertaken, with 20 samples in each stratum.
2. Samples were random variable-radius plots using a basal area factor (BAF) 2 prism wedge to select measurement trees.
3. On each measurement tree the diameter at breast height was measured. If buttressing was present at breast height, a new point of measurement was established above the buttress. Species was also recorded. For common forest types, lookup tables were used to estimate total height and merchantable height. However, for less common forest types, merchantable height was measured in the field.
4. At each field sample an accurate GPS location was captured by placing the GPS in the plot centre and leaving it to average while the plot was being measured. This resulted in the best spatial accuracy and facilitated integration with ASTER data.
5. All field data were entered into the forest assessment toolkit described below.

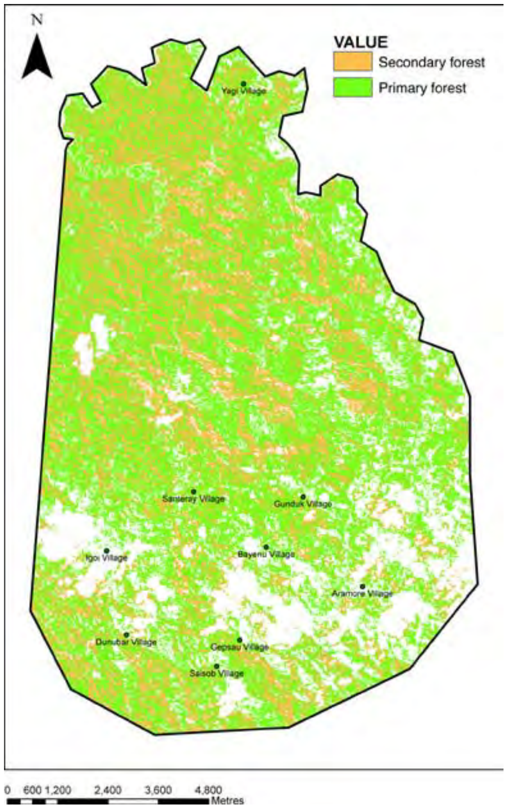


**Figure 2.** Forest classification for Sogi project

During 2008 and 2009, 35 random stratified point sample measurements were taken in the Sogi project area; it was intended that 20 be randomly located in primary forest and 20 in secondary forest. Due to constraints in the field, 19 were located in primary forest and 16 in secondary forest. The entire Sogi project area was accessed using walking tracks to ensure that the sample was spatially representative (Figure 3 shows the Sogi field-sampling team). At each randomly located point sample a BAF 2 prism wedge was used to identify 'in trees', which were measured for diameter, species, merchantable height and distance and bearing to plot centre. Borderline trees were measured and, based on distance and bearing, could be included or excluded during calculations. A hand-held Garmin GPS was left to average at plot centre while measurements were being taken. A forest assessment toolkit described below was used to estimate merchantable timber volume (MV) and forest C in AGLB for the 35 variable-radius plots.

## Digital elevation models

DEMs for project areas were created using the DEM Extraction Module of ENVI. This uses the stereo images of ASTER and ground control points (GCPs) to estimate the elevation of every pixel for a project area. Thirty-five GCPs for Sogi were collected using the spatial location and elevation from hand-held GPS readings taken at plot centres. This DEM was used to estimate hydrology and slope characteristics for the project area using the hydrology tools in ArcGIS.

## Spatial modelling

Ten ASTER spectral bands and 35 point estimates of AGLB and MV were intersected in ArcGIS. Spatial regression modelling could then be used to build a relationship between field measurements and ASTER spectral bands. Dependent variables were MV and AGLB, and independent variables were ASTER bands 1–10.

## ISODATA classification and elevation

A linear regression model was developed for spatial prediction of MV and AGLB. Relationships for observed significant predictors were examined to ensure that a linear model specification was appropriate. The shortcomings of model selection algorithms are well documented (e.g. Nishii 1984), and using a range of selection methods was viewed as the best

Constant communication with landowner communities is vital when conducting fieldwork in Papua New Guinea. Here, everyone poses for a photo after a successful community meeting to discuss field sampling in their tribal lands, Gunduk village, Madang province (Photo: Francis Inude).

**Figure 3.** Sogi field measurement team, September 2008 (Photo: Francis Inude).

way to minimise these shortcomings. Forward, backward and stepwise model selection algorithms were implemented using PROC REG within SAS (SAS Institute Inc. 1996). All selected variables were then entered into the all-possible subsets algorithm, which was used to identify the best model for each subset size. Mallow's Cp and adjusted R-square criteria were used to identify the final models, and candidate models were then vetted for size and sign of coefficients, and logical consistencies to ensure that models were statistically and biologically meaningful.

## Precision of estimates

Using a standard formula (Phillips 1994), we can determine the precision of the estimate of the mean values and the number of plots required to improve precision to desired levels (equation (1)):

$$n = \frac{CV^2 t^2}{E^2} \tag{1}$$

where: $n$ is the number of samples; $CV$ is coefficient of variation; $t$ is Student's t-value for a 95% CI at the specified degrees of freedom; $E$ is the required precision, e.g. within 5% or 10% of the true mean.

Maps and summary information can inform community management and improve decision-making. The information can be used to explicitly compare options for forest utilisation and monetary returns.

## Forest assessment tool

A field data entry and assessment tool has been created in Microsoft® Excel. The assessment tool can be used for data entry and analysis based on the random variable-radius plot inventory described. Here, we describe the biometric models that comprise the tool.

Merchantable volume ($MV$) is calculated from merchantable height ($MH$) and diameter ($D$) assuming a form factor of 0.5 (equation (2)):

$$MV = 0.5\left[\pi\left(\frac{D}{2}\right)^2\right]MH \tag{2}$$

As described above, the hyperbolic height – diameter models was found to perform best for PNG's forests (equation (2)). The field assessment tool uses Excel lookup tables to derive species-specific model parameters for the hyperbolic model (equation (3); Huang and Titus 1992):

$$MH = aD/(b + D) \tag{3}$$

where: $a$ and $b$ are species-specific parameters.

PNGFA merchantability price groups were used to define species as price group 1 (most valuable) to price group 3 (least valuable), and non-merchantable group 0 in a lookup table. MV was assigned to each of the price groups 1 to 3, which were summed to provide a plot-level estimate of MV.

We used the wet tropical forests biomass allometry of Chave et al. (2005) to estimate AGLB for trees on temporary plots (equation (4)):

$$AGLB_i = 0.0776 * \left[\rho_i D_i^2 H_i\right]^{0.940} \quad (4)$$

where: $D_i$ is diameter in cm; $H_i$ is total height in m; and $\rho_i$ is wood specific gravity in g/cm$^3$ for tree *i*. The resulting $AGLB_i$ is the total biomass of the stem, crown and leaves for tree *i* in kg.

We used the ratio of the BAF of the prism wedge (BAF=2) divided by the basal area of the measured 'in tree' to calculate the per ha contribution of the tree (Phillips 1994). This ratio was multiplied by the measurement of interest (MV or AGLB)

Wood density information is required to generate AGLB estimates for all trees on PSPs, and is available for many PNG timber species in Eddowes (1977). Available wood specific gravity (density at 0% moisture content) information from Eddowes (1977) was combined with the compilation for Asian rainforest (IPCC 2006) to derive a species-specific lookup table in the field assessment tool.

Pivot tables are used to generate plot-level summaries of MV and AGLB. The field assessment tool is available for free download at: <http://www.forestscience.unimelb.edu.au/research_projects/ACIAR_Projects/PNG_Project/index.html>.

## Results

Final predictive models of MV and AGLB for the Sogi project are described in Table 1.

Regression models were of moderate strength, explaining 34% and 42% of the variability in MV and AGLB, respectively. Predictors were significant and were similar to those used in the models of Muukkonen and Heiskanen (2007). Average AGLB and MV for 35 plots in lowland tropical forest in the Sogi project area were 92 tC/ha (SD 27.3) and 149.8 m$^3$/ha (SD 47.7), respectively. Averages were within 9.0% and 8.4% of the true mean (90% CI) for MV and AGLB, respectively. These precision estimates (assuming a random sample) satisfy 90% confidence requirements for participating in the Voluntary Carbon Standard (VCS) (VCS 2008a).

### Prediction

The best performing regression models detailed in Table 1 were used to estimate AGLB and MV for every pixel in the Sogi project area. Prediction of merchantable and available timber was based on the PNG Logging Code of Practice that restricts harvesting to areas of less than 30° slope and outside 20-m buffers on streams. The predictions for AGLB and MV are shown in Figures 4 and 5, respectively.

### Resource estimates

Resource estimates for Sogi are provided in Table 2. Based on the forest assessment, there was 1.5 Mm$^3$ of merchantable timber in the 13,113 ha of community forests. Using the DEM to generate hydrology and topography, we could exclude areas from harvesting based on the PNG Logging Code of Practice (i.e. those within 20-m stream buffers and having slopes of more than 30°). Available merchantable timber was reduced to 1 Mm$^3$ comprising an approximate Kwila volume of 37,000 m$^3$ and a mixed hardwood volume of 250,000 m$^3$.

We assessed the estimated total forest AGLB in Sogi as 925,000 t C, of which 620,000 t C was in forest available for harvesting. We can use this to provide an indicative estimate of the AGLB reduction if forest harvesting occurred. Fox et al. (2011) indicated that selective harvesting in PNG resulted in a 55% reduction in AGLB. Therefore, if available forest in Sogi was harvested, AGLB would be reduced from 620,000 t C to 280,000 t C. This corresponds to an approximate AGLB emission of 340,000 t C. This is an indicative estimate only; refer to Fox and Keenan (2011) for a more detailed analysis of C and $CO_2$ emissions from selective harvesting in PNG.

## Discussion

Remote sensing analysis for ACIAR project FST/2004/061 demonstrated that ASTER could be successfully used for mapping forest condition (primary and secondary forest), and spectral information could be integrated with field sampling for forest assessment. This is consistent with the findings of Muukkonen and Heiskanen (2007). An additional benefit of using ASTER data is that they are comparatively cheap ($150 per scene) and easy to source and download. Image acquisition for ASTER is facilitated by an image search facility through the

**Table 1.** Regression models and descriptive statistics for Sogi

| Predictors | Merchantable volume (m³) | | Above-ground live biomass (t C) | |
|---|---|---|---|---|
| | Parameter | Pr > F | Parameter | Pr > F |
| Intercept | 233.941 | <0.0001 | 170.511 | <0.0001 |
| ASTER band 3 | 0.401 | 0.087 | | |
| ASTER band 10 | –2.646 | 0.002 | –1.315 | 0.003 |
| Isodata classification | 8.077 | 0.012 | 3.451 | 0.067 |
| R-square | 0.42 | | 0.34 | |
| Mean—all data[1] | 149.76 | | 92.34 | |
| SD—all data | 47.66 | | 27.28 | |
| Sample size | 35 | | 35 | |
| Samples for 90% CI | 31.37 | | 27.03 | |
| Mean—primary | 162.36 | | 98.91 | |
| SD—primary | 39.08 | | 26.65 | |
| Mean —secondary | 134.79 | | 84.55 | |
| SD—secondary | 53.62 | | 26.74 | |

Sample size: primary 19; secondary 16
[1] All data is the mean for primary and secondary samples combined.

Japanese Space Agency website (http://imsweb.aster.ersdac.or.jp/ims/html/DPR/DPR_Menu.html). The area of interest can be defined, and thresholds for cloud cover can be set. Using this facility, ACIAR project FST/2004/061 acquired level 2B cloud-free images over the four project areas. Level 2B images have been subject to radiometric and geometric correction, and can therefore be projected with other data layers and GPS locations for field data in a GIS system. When integrated with field data entered into a simple Excel proforma for estimation of AGLB and MV, spatial modelling can be used to estimate wall-to-wall forest resources. Forest assessment for community forest management in developing tropical

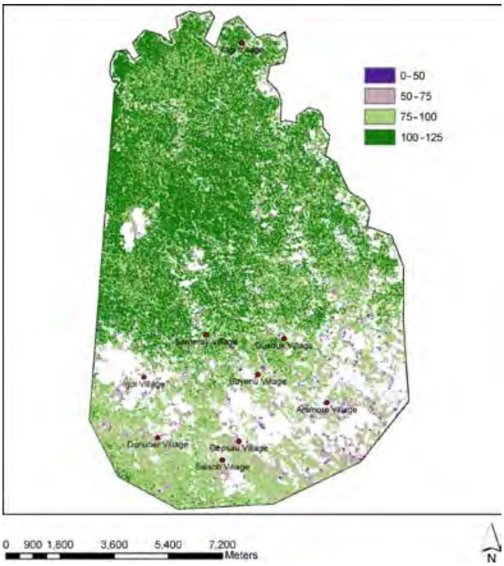


**Figure 4.** Above-ground live biomass prediction for Sogi (tC/ha)

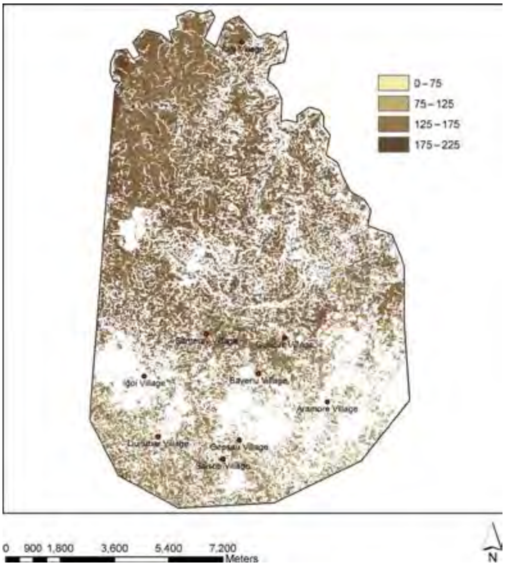


**Figure 5.** Merchantable volume prediction for Sogi (m³/ha)

countries demands cost-effective approaches that can be replicated using simple tools.

Maps and summary information can inform community management and improve decision-making. The information can be used to explicitly compare options for forest utilisation and monetary returns. In the Sogi project area, which contains a large resource of high-value timber species such as *Intsia bijuga* (kwila), this comparison of different utilisation approaches and their monetary returns was very useful in helping the community understand the value of their resource. Assuming that the kwila and mixed hardwoods are the main commercial timber species, we can estimate returns from different utilisation approaches. Large-scale log export operations return K30 kina (K)/$m^3$ to communities for commercial species; therefore, a return of approximately K9m could be expected. However, if the community entered into community forestry with wood products certified as Community-based Fair Trade, returns can be much higher, with kwila returning K900/$m^3$ and mixed hardwoods K600/$m^3$. Therefore, assuming 40% recovery, a return of approximately K13.5m for kwila and K63.4m for mixed hardwoods can be expected. Clearly, the scale and timing of these two utilisation approaches are vastly different, with returns from community forestry spread over a long time horizon—annual production is limited by the manual labour requirements of walk-about sawmills (Grigoriou et al. 2011). However, informing the community of the value of their resource under different production models can help them make decisions.

**Table 2.** Resource estimates for Sogi project area

| | |
|---|---|
| Total area of Sogi (ha) | 13,113 |
| Forest area (ha) | 9,624 |
| Total MV ($m^3$) | 1,500,000 |
| Total AGLB (t C) | 925,000 |
| Available MV ($m^3$) | 1,000,000 |
| AGLB in available forest area (t C) | 620,000 |

MV = merchantable volume
AGLB = above-ground live biomass

Community forest assessment undertaken as part of ACIAR project FST/2004/061 also allowed an estimate of possible alternative revenue from voluntary forest C agreements. Following elements of the VCS (VCS 2008a, b, c) and Intergovernmental Panel on Climate Change (IPCC) guidelines (IPCC 2003, 2006), we can estimate the $CO_2$ emissions associated with commercial timber harvesting in ACIAR project areas, and estimate remuneration under a voluntary C


Presentation of resource information maps to the Sogi community, July 2009 (Photo: Julian Fox).

The Sogi community has constructed a community house from locally milled kwila in Yagi village (Photo: Julian Fox).

agreement. Assuming a conservative C price of K20/ $tCO_2$, this would equate to K12m. Therefore, returns to the community from a voluntary C agreement would exceed returns from a commercial log-export operation (K9m). This is useful information for the community and can inform their decision-making. Community forestry and voluntary C agreements provide revenue and preserve many other values of the forest due to their lower impact.

The intent of forest assessment activities as part of ACIAR project FST/2004/061 was twofold—to develop methodology that could be used by both PNG forest-management agencies for wide area application, and by communities and NGOs to improve community forest management. To satisfy these objectives, an integrated forest assessment system was created in Microsoft® Excel. The forest assessment tool is based on a stratified random variable-radius plot inventory and incorporates lookup tables that facilitate the calculation of plot- and estate-level AGLB (t/ha) and MV ($m^3$/ha). PNGFA is moving to a new preharvest inventory method based on a stratified random variable-radius plot inventory, to replace the 1% stripline inventory, which is both inefficient and biased. Therefore, PNGFA can populate the assessment tool with inventory information for wide-area forest assessment.

## Acknowledgments

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# Assessing the importance of local biodiversity to communities in Madang province, Papua New Guinea

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*Abstract*

The biodiversity of Papua New Guinea's tropical rainforests is utilised by local communities in diverse and often unrecognised ways. Aside from the high commercial value of some rainforest trees, forests provide a number of other goods and services to these communities that are more difficult to quantify; for example, construction, food, medicinal, spiritual, ornamental and recreational values. In addition to being of importance to livelihoods, the forests of Papua New Guinea are among the world's most biodiverse; hence, their valuation, and recognition by local communities, may contribute to their preservation. Our research was carried out in two villages (Yagi and Ohu) in Madang province. The relative value of different components of biodiversity for villagers was estimated according to the pebble distribution method, based on village and gender. The focus groups attributed the highest value for wild plants, in comparison with cultivated plants, wild animals and domestic animals. Interestingly, Ohu focus groups valued wild plants from forests significantly higher than Yagi focus groups. However, there were no significant differences between the opinions of men's and women's focus groups from Ohu and Yagi. Yagi focus groups named 57 taxa as the most important, including *Casuarius* spp. and *Licuala lauterbachii* as those used most commonly. Out of 40 taxa identified by Ohu focus groups, three species (*Pterocarpus indicus*, *Gnetum gnemon* and *Intsia bijuga*) were considered the most valuable, and had a combined relative importance higher than 6%. Some species identified as valuable are common, while others are classified as threatened. Information on rare or threatened biodiversity should be communicated to villagers, coupled with the development of options for sustaining indigenous livelihoods that limit the exploitation of rare local biodiversity.

## Introduction

The global value of Papua New Guinea's (PNG's) biodiversity is often emphasised for the global environmental services it provides (Sekhran et al. 1994; Hunt 2002). It has existence and production value for many people in developed countries, who appreciate the high richness of species and the levels of endemicity (e.g. Miller et al. 1994; Telesetsky 2001). Its role is also emphasised in the development of pharmaceuticals and utilisation in fundamental scientific research (e.g. Telesetsky 2001). However, what value does PNG's biodiversity have for the people who live among it?

Inhabitants of Yagi and Ohu villages, located in Madang province of PNG, agreed to participate in research about the value of local biodiversity for indigenous people. These two villages were chosen as a case study in PNG, a country naturally endowed with high biodiversity that is currently experiencing difficulties in managing its forests, where much of this biodiversity exists. Local communities and biodiversity are interdependent in PNG, and an

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understanding of the importance of different biodiversity components for resource-dependent communities is significant not only for the wellbeing of these people, but also for the conservation of unique PNG biodiversity.

However, literature on the value of biodiversity for subsistence and social activities of indigenous Papuans was published a few decades ago, with no publications (to the authors' knowledge) appearing recently. Since PNG is a developing country, a few decades is a significant period of time for changes in the lifestyles of local people. Furthermore, there is no consensus in opinions about the value of the wild biodiversity for the local communities of PNG. Furthermore, there are few numeric evaluations of the value of biodiversity in the literature.

# Methodology

## Study area

The field research was carried out in two villages (Yagi and Ohu) in Madang province, located on the northern coast of PNG (Figure 1). Yagi village is a case study area for the Australian Centre for International Agricultural Research (ACIAR) project FST/2004/061. It is described as 'moderately accessible' by a Village Development Trust (VDT) Activity Report (2008b). It is situated in primary rainforest approximately 90 km south-west of the main town (Madang) in Madang province. The level of literacy in the village is low because there is a lack of basic education services. There is no health facility in the village and most villagers are subsistence farmers. To earn cash income they sell vegetables, betel nut and the meat of wild animals, as well as coffee, cocoa and vanilla (VDT 2008a). The average income earned by a family per year is K21–50 (kina) (VDT 2008a).

Ohu village is situated approximately 15 km west of Madang. There is an elementary school in the village and the literacy rate is around 80%: however, there is no health facility. The main occupation in the village is subsistence farming and, according to V. Novotny (pers. comm. 2009), annual household income is around K700. The village is proximal (<5 km) to primary (undisturbed) forest; however, local people consider the primary forest to be far away. Wiad Wildlife Management Area (WMA) lies 2 km from the village. This area was established in the customary land owned by the Ohu villagers in the 1990s. It is 322 ha in area with a main purpose of protecting primary forest. In addition, this WMA supports the villagers with cash income collected from tourists and biologists (V. Novotny, pers. comm. 2009; WWF n.d.). Biological research undertaken by The New Guinea Binatang Research Centre in the area also facilitates the villagers' education about nature conservation.

## Pebble distribution method

The field research methodology was based on the pebble distribution method (PDM), a weighted ranking exercise (Sheil et al. 2002). This method helps to identify patterns in the importance of local biodiversity, and stimulates dialogue between participants about their perceptions of biodiversity and its importance to sustaining livelihoods (Anthony and Bellinger 2007). PDM is ideally suited to instances where the illiteracy rate is high, people are not used to complex exercises and the environment is unpredictable (Lynam et al. 2007).

The method uses focus groups of between 6 and 10 people. This size allows one to perform a group exercise and involve all participants in the decision-making (Anthony 2006). It also allows a cross-section of the community to be involved (Sassen and Jum 2007). The people for the groups are chosen either according to the advice of local authorities or simply on a voluntary basis (Anthony 2006; Sassen and Jum 2007). In each stage of the exercise, the group participants are asked to distribute 100 pebbles among labelled cards according to their importance (Sheil et al. 2002). Careful introduction is required to ensure that the participants understand the nature and requirements of the exercise (Lynam et al. 2007).

## Data collection

Two focus groups (men and women) of approximately 10 participants were engaged in the PDM exercise in each of the villages. The participants were divided into men's and women's groups because of the distinct roles of the genders in terms of using biodiversity (Fereday et al. 1994; Petir et al. 1996). Hence, this division allowed differences of opinions between the genders. Figure 2 shows the women's group and Figure 3 the men's group from Yagi village. The informants were chosen on a voluntary basis—all people who wanted to participate were welcome.

First, the importance of domesticated biodiversity was compared with wild biodiversity. The cards were labelled as shown in Table 1. The categories, which were defined according to which environment the

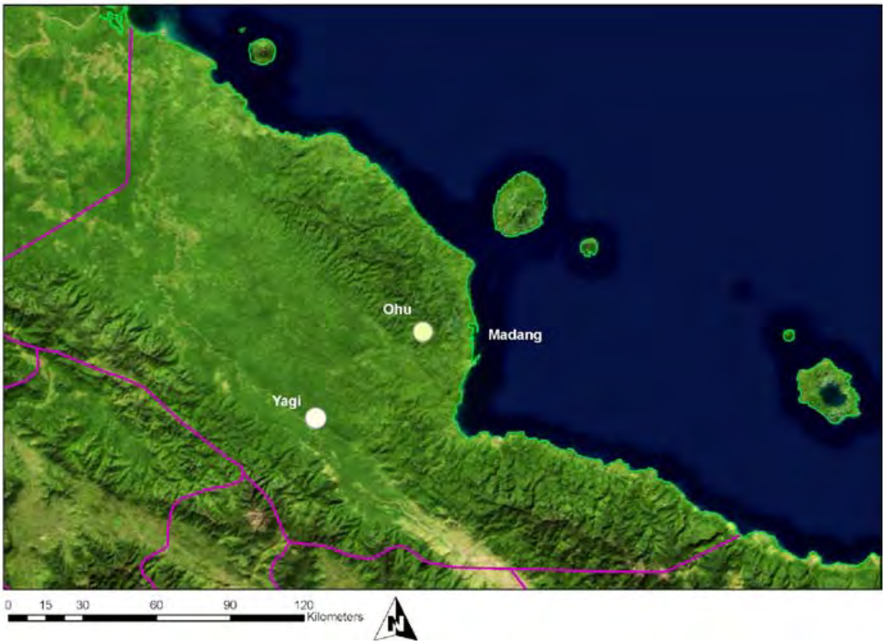


**Figure 1.** Ohu and Yagi villages in Madang province; map background is a Landsat image.

**Figure 2.** Women's group from Yagi village distributing pebbles among use categories (Photo: Dalia Bastyte).

**Figure 3.** Men's group from Yagi village distributing pebbles among use categories (Photo: Dalia Bastyte).

parts of animals, plants or mushrooms were taken, were called 'source categories', adopted from Sassen and Jum (2007) with modifications. This example was used because their research was carried out with people dependent on the goods and services of lowland tropical rainforest, which is similar to the situation in PNG. The categories were modified so that they would cover as much biodiversity as possible but would not overlap.

The use categories for the wild biodiversity were defined according to discussions with the participants. Seven use categories were defined in Yagi village (Table 2). These were arbitrary, chosen to facilitate communication with the participants. The use categories were not compared with one another according to their relative value for the participants; therefore, an assumption was made that they had equal value. The importance of taxa value was based on this assumption.

According to discussions with the participants, the uses of wild biodiversity were grouped differently in Ohu village. Figure 4 shows the women's group from Ohu village, where four use categories were defined (Table 3).

Afterwards, the participants were asked to name the most important wild species according to the use categories. However, some species were identified only to the level of genus and some to even higher taxa (e.g. bamboo), and it was not possible to put a value on a certain species. The names of species were then recorded in both local language and Latin on the cards, and the participants were asked to

**Table 1.** Source categories used for the comparison of wild and domesticated biodiversity

| Category | Description |
|---|---|
| Wild plant from forest | Autochthonous plant growing in the native forest |
| Wild plant, not from forest | Autochthonous plant taken from the native forest and planted in a village |
| Cultivated plant | Plant grown in the gardens—fenced areas outside a village |
| Wild animal from forest | Animal inhabiting native forest, i.e. native species and alien species, for instance, wild pig |
| Wild animal, not from forest | First-generation wild animal caught in a native forest and kept in a village |
| Domestic animal | Animal bred in a village |
| Wild mushroom | Mushroom collected in a native forest (a category of cultivated mushroom in Madang province does not exist) |

**Table 2.** Use categories of wild biodiversity defined in Yagi village

| Category | Description |
|---|---|
| Food and drink | Wild plants, animals and mushrooms used for primary and secondary daily food as well as food used for festivals and ceremonies, and drinks made from wild plants |
| Construction | Parts of wild plants used for building houses and fences |
| Medicine | Wild plants, animals and mushrooms used for treating diseases |
| Ornaments | Wild plants and animals used for planting in the village as aesthetic plants, shade trees; and for making clothes, adornments and decorations for everyday life, festivals and traditional dances |
| Recreation | Wild plants and animals used for leisure and recreation |
| Magic | Wild plants and animals used for coping with inimical spirits and malevolent people |
| Tools | Parts of wild animals and plants used as household and garden utensils |

**Table 3.** Use categories of wild biodiversity defined in Ohu village

| Category | Description |
|---|---|
| Food and drink, daily uses | Wild plants, animals and mushrooms used for primary and secondary daily food, and drinks made from wild plants |
| Ceremonies | Anything made from wild biodiversity and used for special occasions: wild plants, animals and mushrooms used for food and drinks for festivals and ceremonies; parts of animals and plants used for adornment and decorations during festivals and traditional dances; parts of animals and plants used for musical instruments; wild biodiversity used for magic |
| Medicine | Wild plants, animals and mushrooms used for treating diseases |
| Construction | Parts of animals and plants used for building houses and fences, and making tools |

distribute the pebbles according to the value that each species had for the community in the use category under consideration. The first village in which the exercise was performed, Yagi, refused to do this part of the exercise, explaining that they already felt tired. Hence, evaluation of numeric importance of particular species was given only by Ohu people, which reduced the dataset for the most detailed part of the research.

## Data analysis

*The source categories*

Data were analysed using SPSS statistical package, Microsoft® Excel and the descriptive discourse method. The value that people put on the source categories was compared according to their mean percentages. Independent sample t-tests were used to compare the mean values across gender and village. Descriptive

**Figure 4.** Women's group in Ohu village distributing pebbles (Photo: Dalia Bastyte).

discourse was used to compare the opinions of the men's and women's groups about the source categories in Ohu and Yagi.

*The use categories*

The taxa that Yagi people identified as the most important were put into a matrix according to the use categories, and compared with one another according to the number of use categories to which they belonged. The taxa that Ohu people named as the most important for use categories were put into a matrix, and individual use value (IUV) was calculated by summing up the values attributed for that species in all the categories. Combined relative importance (CRI) for each taxon was calculated by dividing IUV by the total possible value (TPV). TPV was calculated by summing the values that both groups put on all four categories (in this case it was 800).

# Results

## Comparison of the villagers' opinions about wild and cultivated biodiversity value

The mean relative value of the four source categories was compared. Mean relative value was calculated using data from all four groups (men's and women's groups in Yagi and Ohu). The category of wild plants clearly has the highest value for the villagers, being assigned almost half (48.75%) the mean value for all source categories combined (Table 4).

## Comparison of Ohu and Yagi

Comparing opinions about the value of wild and cultivated biodiversity between Ohu and Yagi indicated a significant difference for one source category. An independent sample t-test showed that opinions about wild plants from the forest were significantly different ($t = 8.497$, $df = 2$, mean difference = 9.50, $p < 0.05$)—Ohu groups attributed significantly greater importance to the category of wild plants from the forest than Yagi groups (Figure 5). Comparing opinions about the value of wild and cultivated biodiversity of different gender groups indicated no statistically significant differences (Figure 6).

## Men's and women's opinions about wild and cultivated biodiversity value

Looking in more detail, men's and women's groups' opinions about seven local biodiversity source categories (Figures 7 and 8) can be described.

**Table 4.** Mean value of local biodiversity source categories for Ohu and Yagi groups

| Source category | Composition of the category | Mean relative value (%) |
|---|---|---|
| Wild plants | Wild plants from the forest, wild plants grown in the villages, and mushrooms | 48.75 |
| Cultivated plants | Plants grown in the gardens (subsistence farming areas outside a village) | 25 |
| Wild animals | Wild animals either from the forest or not from forest (i.e. first-generation wild animals that were tamed) | 18.25 |
| Domestic animals | Domesticated animals | 8 |

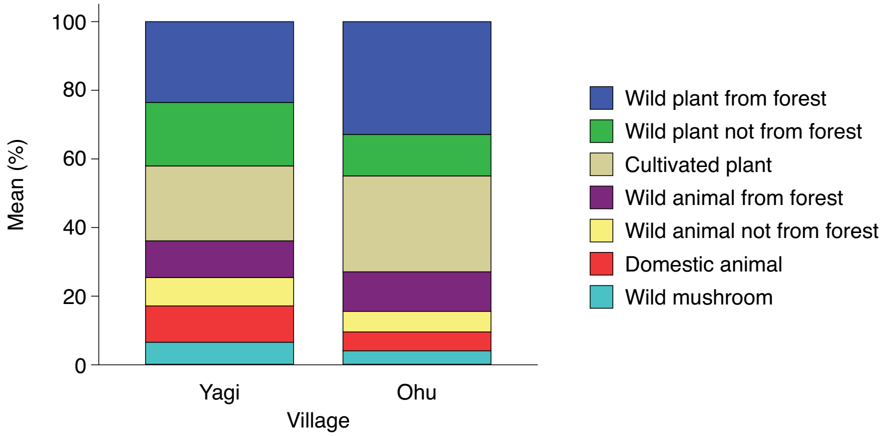


**Figure 5.** Mean values of weighted ranks for biodiversity source categories in Yagi and Ohu villages

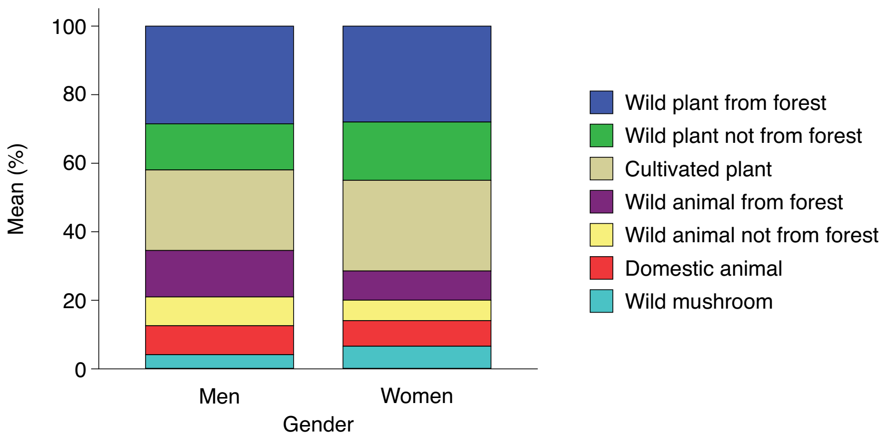


**Figure 6.** Mean values of weighted ranks for biodiversity source categories for men's and women's groups

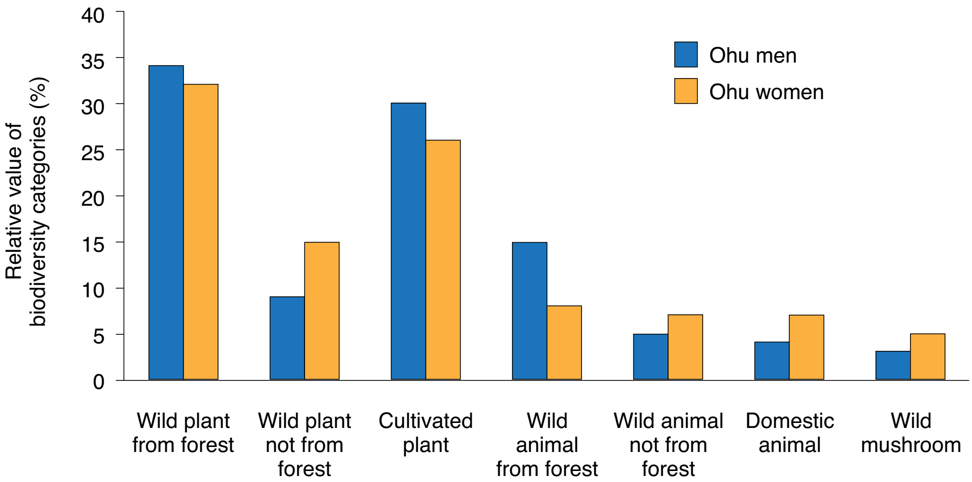


**Figure 7.** Value attributed by Ohu men's and women's groups for biodiversity use categories

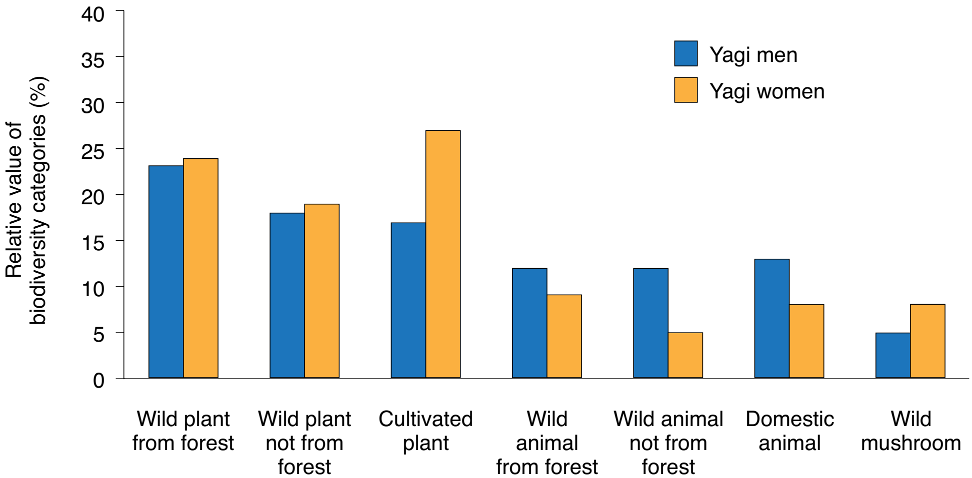


**Figure 8.** Value attributed by Yagi men's and women's groups for biodiversity use categories

## Ohu village

We found no significant differences between men's and women's groups' opinions in Ohu village. Ohu men noticed that wild plants from the forest can be used for multiple purposes: for medicine against a runny nose, a fruit to eat, a plant containing water to drink, bark of a tree to get rid of the spirits that affect people or to treat a snake bite, materials for drums used for local communication, bird feathers for traditional dances, ginger to improve the taste of food, plants to fence a garden or a vine for construction. Moreover, people are even more dependent on these plants in unfavourable conditions, for example in periods of drought. The Ohu women's group

Hunting of local fauna is an important source of protein in remote areas but can have significant impacts on local biodiversity. Here, youths from the Kiriwa tribe of Simbu province, Papua New Guinea, have caught a cuscus (family Phalangeridae) (Photo: Julian Fox).

confirmed the men's opinion—wild plants from the forest are used for many purposes.

It was agreed that wild plants not from the forest were not as important as the ones from the forest. It was explained that some of these plants are used for food; for example, the leaves of *Gnetum gnemon* are often used as greens in the staple food. Also, some of the wild plants are used decoratively in the village. Cultivated plants were explained to be important because they are used for daily consumption as food, and in festivals and as a bride price.

Ohu people explained that wild animals are hunted in the forest on occasions. Pigs, cuscuses and wallabies are hunted for festivals and ceremonies. For example, before harvesting food from a new garden, people go to hunt a wild pig or catch crabs, fish, prawns and lobsters from a river. Also, wild animals are used for cultural ceremonies called 'sing-sing'; for example, birds of paradise are a key item for traditional dancing—without their feathers, traditional dancing cannot happen. Lizards are also important for cultural ceremonies because their skin is used for kundu drums, which are the main traditional musical instruments in Madang province. Since these animals are not used every day, the value they were given was not as high as for the plants. Offspring of some animals can be taken from the forest and kept in the village, for example pigs, cuscuses and hornbills. However, it does not happen very often, and the category of wild animals not from the forest was therefore not highly valued.

Domestic animals were not attributed with a very high value because they were not employed very often. Itemising why they attributed a low value for domestic animals, Ohu people explained that dogs are used for guarding a house and hunting, pigs mainly for a bride price and sometimes sold for cash income, chickens for food, and cats for protecting houses against rats.

Mushrooms were valued the least of all the categories. It was explained that they are used only for food and as a medicine, but not for a wide range of diseases. Moreover, they can be used only in season, which is a short period.

## Yagi village

The opinions of men's and women's groups in Yagi diverged more than in Ohu. In particular, the women's group seemed to value cultivated plants more than the men's. In explanation, Yagi women answered: 'This is what we use from the morning till the night every day'. However, the men explained that, even though cultivated plants are used for food, as building materials and as medicine, their seedlings have to be bought in a market, making it is difficult to access them. Furthermore, because people have used wild plants from the forest for longer than cultivated plants, they became more accustomed to those plants, and therefore they have more uses. Moreover, only wild plants from the forest are used for magic and this is a very important purpose. (It has to be mentioned here that magic is practised only among men, while gardens are usually worked by women in Madang province.)

Yagi people named quite a few uses for wild plants not from the forest: for food, medicine, as building materials, as aesthetic ornamental plants, as trees providing shade in the village and for selling in a market. Wild mushrooms in Yagi village are used only for food and only in season, so they have less value for the people than other categories.

Wild animals from the forest were used for many purposes; for example, for food, exchange, selling in markets, and for kundu drums and headdresses. However, people explained that wild plants from the forest were much easier to access than animals. Hence, the animals are caught when people find them, but it does not happen often. Therefore, the people usually use plants. It is interesting to notice that, even though Yagi people specified that they use wild animals rarely, they also listed that they use domestic animals even more rarely than wild animals. The lack of substitution increased the value of wild animals from forest.

The importance of the wild animals not from the forest category was explained similarly as for the wild animals from the forest. Various animals are caught and kept in the village for different purposes: as pets, used for food, as bride price payment, sold in the markets, and their feathers used for headdresses and their bones as utensils. The value of domestic animals in Yagi village was explained similarly as in Ohu village: they are used for bride price payment, for food, as pets, cats for chasing rats, dogs for security and hunting, and buffaloes for pulling a carriage. In addition, their feathers are used for decorations and chasing mosquitoes, and parts of the animals are used for necklaces. However, they are used relatively rarely.

### Uses of wild biodiversity in Yagi

According to conversations with the villagers, uses for wild biodiversity in Yagi village were grouped into seven categories (Table 2). The participants were asked to name the most important species in each use category. It was found that *Casuarius* species and *Licuala lauterbachii* have many uses, with these species belonging to four use categories. Six taxa belong to three use categories, namely *Artocarpus communis,* bamboo, cuscus, *Intsia bijuga, Mucuna* sp. and *Pometia pinnata.* There were 20 taxa named that belong to two use categories and 29 taxa that belong to one use category in Yagi village.

### Uses of wild biodiversity in Ohu

According to conversations with the villagers, uses for wild biodiversity in Ohu village were grouped into four categories (Table 3). CRI for all taxa are presented in Table 5.

Table 5 shows that the CRI of the 40 taxa that the participants from Ohu village indicated as the most valuable range from 0.6% to 7.1%. Some species have high CRI because they are used in several categories, and others because they are highly valued in just one or two use categories. The most valuable species, *Pterocarpus indicus,* was not only present in all use categories, but was also given high value in each of the categories. The second most valued species, *Gnetum gnemon,* was used in two use categories, but was given higher value in the categories it was used in than the majority of the other taxa.

## Discussion

### Wild and cultivated biodiversity value

Economic variables are an imperative factor defining the value of biodiversity for indigenous people. The gross domestic product per capita of PNG is estimated as K2,586.25, but the income is distributed very unequally (National Statistical Office of PNG 2000; Forest Trends 2006). Less than 10% of PNG's population over the age of 10 years works in salaried employment; therefore, for the majority of Papuans, subsistence activities, which are occasionally supplemented by market sales, are the only means of survival. The sources of subsistence named in the literature are: agriculture, hunting, gathering and fishing (Fereday et al. 1994). Observing day-to-day life in PNG, it is not difficult to notice that the sources for market sales are the same as for subsistence. There is no doubt that subsistence activities are vital to sustain livelihoods in PNG, but opinions diverge about the value of each subsistence activity for local communities.

It is generally accepted that agriculture is the main source for sustaining livelihoods in PNG villages, where 84% of the population lives. The importance of agriculture is stressed because it provides the people with staple food (Fereday et al. 1994; National Statistical Office of PNG 2000), while hunting and gathering is claimed to be only a subsidiary activity (Bulmer 1972). However, while emphasising the need to secure a supply of staple food, other needs of indigenous people are often unvalued.

According to Ohu and Yagi people, local biodiversity is used for multiple purposes. Most noticeably, wild biodiversity has a wide range of uses because

**Table 5.** Combined relative importance for the wild biodiversity taxa in Ohu village

| Taxon | Food and drink, daily uses | Ceremonial | Medicine | Construction | Total |
|---|---|---|---|---|---|
| *Pterocarpus indicus* | 0.0125 | 0.0125 | 0.0225 | 0.02375 | 0.07125 |
| *Gnetum gnemon* | 0.0375 | | 0.02875 | | 0.06625 |
| *Intsia bijuga* | 0.0175 | 0.01125 | | 0.03375 | 0.0625 |
| *Vitex cofasus* | 0.0075 | 0.025 | | 0.0225 | 0.055 |
| *Pometia pinnata* | 0.02 | | 0.00875 | 0.02375 | 0.0525 |
| *Cinnamomum grandiflora* | 0.0125 | 0.01375 | 0.025 | | 0.05125 |
| *Arenga microcarpa* | 0.0175 | 0.0275 | | | 0.045 |
| *Ficus copiosa* | 0.0275 | | 0.0125 | | 0.04 |
| *Cordyline terminalis* | | | 0.0325 | | 0.0325 |
| *Caryota rumphiana* | 0.01375 | 0.00875 | | 0.00875 | 0.03125 |
| *Metroxylon sagu* | | 0.03125 | | | 0.03125 |
| *Alphitonia incana* | | | | 0.02875 | 0.02875 |
| *Amomum aculeatum* | | | 0.02625 | | 0.02625 |
| *Melanolepis multiglandulosa* | | | 0.02625 | | 0.02625 |
| *Paradisaea* sp. | | 0.02625 | | | 0.02625 |
| *Flagellaria indica* | | | | 0.025 | 0.025 |
| *Ficus dammaropsis* | 0.02375 | | | | 0.02375 |
| *Ficus wassa* | 0.0225 | | | | 0.0225 |
| *Calamus aruensis* | | | | 0.02125 | 0.02125 |
| *Premna obtusifolia* | | | 0.02125 | | 0.02125 |
| Bamboo | | | | 0.02 | 0.02 |
| *Sus scrofa papuensis* | | 0.02 | | | 0.02 |
| *Rhyticeros plicatus* | | 0.015 | | | 0.015 |
| *Ficus nodosa* | | 0.01375 | | | 0.01375 |
| *Tabernaemontana aurantiaca* | | 0.01375 | | | 0.01375 |
| *Hydriastele costata* | | | | 0.0125 | 0.0125 |
| *Mucuna* sp. | 0.0125 | | | | 0.0125 |
| *Musa* sp. | | | 0.0125 | | 0.0125 |
| *Piper betle* | | | 0.0125 | | 0.0125 |
| *Zingiber officinale* | | | 0.0125 | | 0.0125 |
| *Calopogonium* sp. | 0.01125 | | | | 0.01125 |
| *Donax canniformis* | | | | 0.01125 | 0.01125 |
| Lizard | | 0.01125 | | | 0.01125 |
| *Cacatua galerita* | | 0.01 | | | 0.01 |
| Cuscus | | 0.01 | | | 0.01 |
| *Randia decora* | | | | 0.01 | 0.01 |
| *Cassia alata* | | | 0.00875 | | 0.00875 |
| *Celtis latifolia* | | | | 0.00875 | 0.00875 |
| *Sterculia sp* | 0.0075 | | | | 0.0075 |
| *Uncaria* sp. | 0.00625 | | | | 0.00625 |

the people are more accustomed to it. The first example of the direct use value of local biodiversity for indigenous people is enrichment of the diet with proteins and vitamins. Another example is medicinal purposes. There are no health facilities in these villages, so the people depend principally on local plants for the treatment of diseases. Even though cultivated plants are sometimes used for medicine, wild species are used much more often. One more important example is construction materials. Houses and fences protecting the gardens in Yagi and Ohu are built from local plants, again mainly of wild origin.

Besides economic importance, wild products have a value for other aspects of indigenous life. For example, feathers of the bird of paradise, which are used for traditional dances, were declared as 'not for sale' by Ohu villagers. PNG is famous for its cultural diversity. More than 800 distinct languages exist and a similar number of different cultures are present in the country (Thomas 2003; WWF 2006). According to Yagi and Ohu people, a number of the wild species are used for traditional festivals and magic, which are key to maintaining local cultures. These species cannot be replaced by market goods.

Because of these two reasons—direct importance for sustaining livelihoods and value for cultural activities—wild plants and animals were highly valued by the Yagi and Ohu focus groups (Table 4). Interestingly, Ohu focus groups valued wild plants from the forest significantly higher than Yagi focus groups. Ohu village is much closer to the main town of the district (Madang) than is Yagi village. This has several implications for the villagers. First, people can more easily commute to the town and therefore have higher income, which means that they become less dependent on local biodiversity. Second, it is easier to maintain a school and get health care closer to the town. Education might have an impact on the people's attitudes about the value of the biodiversity. Third, the environment around Ohu is experiencing larger anthropogenic impacts than around Yagi. Yagi is situated in primary forest and Ohu people

It is common in Papua New Guinea for local biodiversity to be caught and raised in the village. Here, a young cassowary (*Casuarius* sp.) is being raised as a pet in the Sob community, Madang province (Photo: Julian Fox).

Papua New Guinea has a rich diversity of local cultures. At the Goroka Show this diversity is on display, with the many cultures of the highlands exhibiting their tribal dances (Photo: Julian Fox).

perceive that primary forest is far away. However, according to J. Fox (pers. comm. 2009), Papuans are strongly attached to their traditional environments. This attachment to the primary forest that formerly surrounded the village but has become more distant could have exaggerated the value of species contained in primary forest for Ohu villagers.

One more result of this research worthy of discussion was the similarity of opinions between the genders. There were no significant differences between the opinions of men's and women's focus groups. It appears that, despite the different traditional roles in PNG society, men and women tend to have similar opinions on the importance of biodiversity source categories for their communities. One exception were Yagi women, who valued cultivated plants as 27%, while Yagi men valued this source category as only 17%. This result is intuitive because women traditionally spend most of their time in the gardens, whereas men have different occupations. For example, according to research done by Anthony and Bellinger (2007), people from a traditional society in South Africa valued the landscapes where they themselves spent most of their time as the most important for their community. However, this tendency did not emerge in Ohu village. The current research cannot explain this, but it could be that Ohu villagers are more influenced by urban attitudes and the traditional roles in the village are expressed to a lesser extent.

## The value of wild taxa

### *Yagi village*

Yagi focus groups identified *Casuarius* spp. and *Licuala lauterbachii* as the taxa used for most (4) use categories. Two species of genus *Casuarius* (*C. bennetti* and *C. unappendiculatus*) inhabit the forests of Madang province. The exact species was not identified during the discussions with Yagi villagers; therefore, both species are reviewed below.

*Casuarius* species (cassowary) belong to the order Struthioniformes. They are ratites; that is, large, flightless birds of archaic origin. Cassowaries need large areas of thick tropical or subtropical forest as their habitat. Because of its important role in the tropical forest ecosystem, cassowary is acknowledged as a keystone species (Wet Tropics Management Authority 2006). However, both *C. bennetti* and *C. unappendiculatus* are included in the International Union for Conservation of Nature and Natural Resources (IUCN) Red List (IUCN 2008).

*Casuarius bennetti* (dwarf cassowary) is endemic to the island of New Guinea. According to the IUCN Red List, these birds have a status of near threatened. The population of *C. bennetti* is declining mainly because of heavy hunting pressure (IUCN 2008).

*Casuarius unappendiculatus* (northern cassowary) has a narrower distribution than *C. bennetti*, being restricted to the northern lowlands of New Guinea. Its habitat is rainforests in river floodplains. Northern cassowary constitutes a major food source for subsistence communities, and has a major cultural importance. However, no breeding of domesticated birds exists. Because of its high value for indigenous people and its unsustainable consumption, the species has a status of vulnerable in the IUCN Red List. It is claimed to be 'dependent on the local culture and the availability of weapons and alternative meat-sources' (IUCN 2008).

People from Yagi stated that they use *Casuarius* spp. for food and the manufacture of tools. Parts of these birds are also used for traditional dances and magic. (People from Ohu mentioned several times during the exercises that they would like to include cassowary as a valuable species, but cannot because this species does not live in their forest anymore.) It seems that cassowary is one of the most valuable species for indigenous people. However, the consumption habits seem to be unsustainable and when human populations reach higher density, the species ceases to exist in surrounding forest. According to the researchers from Binatang Research Centre, the animal's density in PNG is inversely proportional to people density. The more villages in the area, the bigger they are and the closer the towns, the fewer animals live in the surroundings.

*Licuala lauterbachii* is an indigenous palm of PNG and Solomon islands (Riffle and Craft 2003). Yagi people use it for construction, and the stem is split and sharpened into spears for hunting. Leaves are used as decorations for traditional dancing. This tree is not threatened according to IUCN and it is a common tree in the undergrowth of rainforests (Riffle and Craft 2003).

The two species mentioned above illustrate the general situation. Some of the species that Yagi focus groups identified as valuable are common, while others are threatened.

*Ohu village*

Out of 40 taxa Ohu focus groups identified as the most valuable, three species (*Pterocarpus indicus, Gnetum gnemon* and *Intsia bijuga*) had a CRI higher than 6%. These species and their uses are described below.

*Pterocarpus indicus* (red sandalwood), in comparison with abovementioned species, has a wide distribution. It is local in south-eastern Asia, northern Australasia and the western Pacific Ocean islands. This huge (30–40 m tall and up to 2 m in diameter) deciduous tree is used for many purposes. It is a hardwood species and its timber is highly valued because of its resistance to decay and its decorative appearance. The flowers and leaves of the tree are eaten, parts are used for medicine, and the tree itself is used ornamentally (Traditional Tree Initiative 2006a).

Red sandalwood is extinct in some parts of its original range, while in other parts this species is heavily exploited and its population is decreasing. Therefore, its status in the IUCN Red List is defined as vulnerable. The largest remaining subpopulation is in New Guinea (IUCN 2008). Ohu focus groups identified *Pterocarpus indicus* as important for daily food, ceremonies, medicine and construction.

*Gnetum gnemon* (gnetum = two-leaf) is a native tree in Indo-Malaya and Melanesia, but currently it is also widespread in south-eastern Asia and the Pacific islands. This species is tolerant to various environmental conditions. It is an important agroforestry species—its timber, leaves and nuts are widely used. In Melanesia this tree is used for food, cordage, timber and medicine (Traditional Tree Initiative 2006b). Ohu people identified it as an important species for daily food and medicine.

*Intsia bijuga* (kwila or Borneo teak) is distributed through south-eastern Asia and the islands of Melanesia, Micronesia and Polynesia. The tree is claimed to be one of the most highly valuable species in its range because of its cultural importance and value as commercial timber. It is used as a timber, medicine and craft wood for high-quality carving (Traditional Tree Initiative 2006c). Because of its immense importance, the tree has been exploited so heavily that only a few large natural stands remain. Therefore, it is classified by IUCN as vulnerable

(IUCN 2008). Ohu people use *Intsia bijuga* for construction, food and ceremonies.

Two out of three of the most valuable species identified by Ohu participants are classified as vulnerable in the IUCN Red List because of overconsumption. Even though one of the participants revealed personally to the researcher after the PDM exercise that the species will never go extinct because indigenous people know the magic spells to invite species back when they are needed, the IUCN Red List suggests that a threat for the most valuable species exists. Some of these species are threatened because of the activities of local people, but others because of the unsustainable harvesting practices. However, 97% of the PNG land area belongs to traditional owners according to customary land tenure, and only traditional owners can decide which actions can be implemented on their land.

## Conclusions

It is evident that tropical forests are not only one of the most biologically diverse terrestrial ecosystems, but also one of the most threatened. Growing demand for wood and its derivatives, coupled with demand for land for food production due to population growth, poses an increasing threat to the tropical forest frontiers. As a result, 75% of remaining frontier forest outside the boreal region is threatened (Sizer 2001).

Local communities living in the tropical forests have to be mentioned in a discussion of global threats to tropical forest biodiversity. First, the forests that are threatened have a value for these communities, which is a strong reason for conservation of the forests (Sheil and Wunder 2002). Second, biodiversity to some extent depends on indigenous people. As Toledo (2001) notes, 'they hold a key to successful biodiversity conservation in most of the biologically richest areas of the world'. Therefore, understanding the needs of indigenous people is an essential condition for biodiversity conservation.

The biodiversity of PNG's tropical rainforests is used by local communities in wide-ranging and often unrecognised ways. Aside from the high commercial value of some rainforest trees, forests provide a number of other goods and services to communities that are more difficult to quantify; for example, construction, food, medicinal, spiritual, ornamental and recreational values. The focus groups from Ohu and Yagi villages highly valued local wild biodiversity. They explained that it can be used for more purposes than cultivated biodiversity. Some of the purposes are very important (e.g. magic), and the species used cannot be replaced. Moreover, people are even more dependent on the wild biodiversity in unfavourable conditions; for example, in periods of drought.

However, some of the species identified by the focus groups as valuable are included in the IUCN Red List (e.g. *Casuarius* spp., *Pterocarpus indicus* and *Intsia bijuga*). Hence, the populations of these species decline, and a risk emerges that the communities will not be able to use them any more in the future. Some of the valuable and threatened species are acknowledged as keystone species; that is, they have a large, stabilising influence throughout an ecosystem and determine the survival of many other species (e.g. *Casuarius* spp.). Communicating the existing situation to the communities could be helpful to reduce the consumption of such species to a sustainable level.

This research showed that different communities value the sources of local biodiversity differently. Ohu groups valued wild plants from the forest significantly more than Yagi groups. The question why there were differences in opinions between Ohu and Yagi focus groups remains unanswered. One more area open for further research is the differences between the opinions of genders. This research does not show significant differences between the mean values of Ohu and Yagi men's groups with Ohu and Yagi women's groups; however, a bigger dataset could show different results.

An understanding of the importance of different species/taxa for resource-dependent communities is significant not only for the wellbeing of these people, but also for the conservation of biodiversity. This understanding is needed for developing biodiversity conservation policies. Policies that recognise and incorporate the needs of local villagers are more likely to be adopted by these people, who have a significant influence on local biodiversity (Anthony and Bellinger 2007).

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# Improving forest inventory in Papua New Guinea: moving away from the 1% stripline survey

**Cris L. Brack[1]**

*Abstract*

Stripline inventories have been used for some time in Papua New Guinea (PNG) and, in 1991, requirements for inventory covering 1% of the forest estate were included in the Forestry Act. The requirement was related to the need to generate resource maps as well as estimate total wood product potential to promote good forest management. However, these inventories have never been adequately resourced or able to produce the unbiased and precise estimates or maps required for forest planning or policy. Alternative approaches that exploit the remotely sensed data now available can replace the stripline approaches, producing unbiased estimates and maps of the resource with substantially less on-ground field work required.

These alternatives include statistically robust approaches such as multistage sampling (especially stratified random sampling), when the remote sensing tools can map out only relatively homogeneous patches of forest. The cost of field work can be further reduced using cluster sampling, also very robust when applied in a systematic way, and optimal allocation of sample numbers to strata. Where the remote sensing data can detect variation within these 'homogeneous areas', multiphase systems can be used to provide even more precise estimates of mean resources as well as detailed maps of the resources. Point-sampling approaches have also been demonstrated to provide precise, unbiased and cost-effective estimates of wood products, stocking and some biodiversity indexes.

This paper outlines options for using multistage and multiphase sampling approaches in PNG to provide good forest-management information more cheaply and with more statistical rigour than the 1% stripline approach. Examples from subtropical and temperate forests are provided to demonstrate the operational potential of the various options. Given the increasing scrutiny of legality for large- and small-scale forest operations, it is recommended that the current legislation is amended to provide greater flexibility in specification of forest inventory designs, based on measures such as desired accuracy, that will allow the use of more-efficient sampling approaches.

## Introduction

Systematic collection of information about a resource often begins as a management response to a perceived shortage. For example, systematic mapping of European forests began in the late 18th century following a fear that fuelwood resources from forests accessible to the growing city centres would soon be exhausted (Brack 1997). These first forest maps just delineated areas of forest and were made to assist planning and management of the scarce resource. By the beginning of the 20th century these simple maps were supported by stripline approaches to collect statistically based estimates of total forest population values (Figure 1). These approaches were particularly relevant for planning the large and unmapped forest resources in North America and Australia as they allowed the creation of maps as well as an unbiased estimate of the total forest resource. Throughout the century, however, major advances in

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technology (including aircraft, satellites and computers), coupled with advances in sampling theory, allowed the development of approaches that could provide superior maps and more-precise estimates of population values. By the end of the century, forest quantification approaches existed that produced spatially explicit, unbiased and precise estimates of forest resources while substantially reducing the need to collect measurements 'on the ground' in a traditional forest mensuration sense (Brack 2003). In the 21st century further technological and theoretical advances are already being produced that will substantially enhance the quality and scale of forest information to allow improved management.

This paper briefly reviews the implementation of a stripline approach designed to support forest management in PNG. Alternatives that can now be used practically to improve the management information are then explored.

## Forest inventory plot system of PNG

### Original design and purpose

The Forestry Act 1991 s. 47(1,2) sets out a standard of a 1% (by area) systematic sample measurement to support national, provincial and forest-level planning. These sample measurements were to support the determination of allowable cuts and, at forest-level, to plan the creation of maps that detailed the cutting patterns (expected volumes over specific areas cut each year) over a 35-year horizon. The decision to use striplines to cover 1% by area must be related more to the potential creation of useful maps than to the desire for a given level of accuracy in the estimates of wood volume. The precision or accuracy of volume estimates from randomly or systematically selected plots is related to the number of samples, not the percentage measured, and

Increasing demand for quality and quantity of information

| Sources of information and collection techniques | Year | Requirements and technologies affecting forest inventory |
|---|---|---|
| Maps of areas of forests | 1800 | Perceived shortage of fuelwood (central Europe) |
| Visual estimation of timber over small areas | 1825 | |
| Random stripline surveys. Tree volume tables developed | 1850 | |
| Statistically sound surveys developed | 1875 | |
| Forest mensuration relationships increasingly used, e.g. volume:basal area | 1900 | Increased demand for information over large areas in North America and Australia |
| Stratified sampling, serial survey | 1925 | Major advances in technology including aircraft devices and computing devices |
| Textbooks on statistically based survey methods. Variable probability sampling (plotless cruising) | 1950 | Increasing demand for multiple resource information and information to aid large industry developments |
| Maps of areas of forests | 1975 | Microcomputers and GIS become freely available |
| Multiphase, multistage inventories. Linear and nonlinear regression models. Expert systems | 2000 | Increasing concern over biodiversity and ecologically sustainable development |
| | 2025 | |

Increasing cost of human labour • Decreasing cost of technology

**Figure 1.** A time line of major developments in forest information collection (Brack 1997)

sample numbers in the order of 100 plots are often considered sufficient to gain precise and unbiased estimates. Enough striplines to cover 1% of the PNG forest resource would result in more plots by orders of magnitude than required for accurate estimates of overall mean volume.

A forest inventory plot system (FIPS) was initially envisioned as a series of systematically placed striplines across the majority of PNG's forest estate. These striplines are comprised of a continuous strip of rectangular 'plots' and were expected to be parallel to each other to aid in the construction of maps. Plots were of two widths—merchantable and non-merchantable trees were measured within a 0.2 or 0.1 ha area, respectively. The distance between lines of plots would be set to ensure that 1% of the area (occupied by merchantable trees) was covered. Trees within each plot were measured or otherwise assessed for diameter at breast height (dbh), merchantable height, species class and form class. Sketch maps associated with each plot divided the area into accessible or non-accessible zones and other operational characteristics. Such an inventory system would allow resource maps to be constructed to provide an indication of species, volume and operational characteristics for each concession area.

### Current implementation and use

Unfortunately, it appears that restrictions in infrastructure and inventory crews meant that the systematic and parallel placement of striplines across the national estate was not feasible. In an attempt to maximise the area sampled by striplines and thus approach the mandated 1% sampling intensity, striplines were placed to maximise the use of existing infrastructure (e.g. road or other access). This subjective placement means, however, that, even while allowing a greater percentage of the forest area to be sampled, the probability of selection for any stripline cannot be calculated. Without an estimate of selection probability, all the traditional forest sampling approaches (e.g. random, systematic, multistage, multiphase, variable probability) cannot be used, and there is no generally acceptable method to estimate the mean, total or precision of the population from the stripline statistics.

Also, while these subjectively placed striplines may allow users to draw up resource maps or estimate the fraction of land that is non-harvestable in the area between the lines, such maps and estimates cannot be extrapolated outside the small selected area. There does not appear to have even been any regular exploitation of the subjectively placed striplines to draw up these restricted maps.

## Alternatives to 1% striplines

### Assumptions

Stripline approaches essentially make the assumption that maps of the resource distribution are needed but do not exist. The approach creates the required map using systematic observation along lines that are close enough to allow interpolation between them, either by eye or using geospatial techniques such as kriging. Maps do, however, now exist for a number of scales over the extent of PNG. These maps can delineate forest/non-forest and recently disturbed (regularly updated by remote sensing) and broad forest types at a minimum. Under many circumstances, areas delineated within these forest types and disturbance boundaries may be assumed to be relatively homogeneous, and practical sampling systems that provide more precise estimates of population totals at cheaper costs than stripline surveys are available. Alternatively, the remote sensing platforms may provide a wide range of auxiliary information that may be used determine patterns within the above 'homogeneous' areas (called strata). More powerful and efficient sampling systems can be used where this auxiliary information is related to the forest resources of interest.

The requirement of a 1% by area sampling intensity to assist in the creation of maps must be replaced. The replacement standard could be a combination of sampling confidence limits around the mean parameter estimates (e.g. 95% of the time, the true population mean will be within ±10% of the mean estimated by the sample) and the accuracy of the boundaries on the maps derived by the remote sensing (e.g. 95% of the time, the true boundary will be within 25 m of the boundary shown on the map).

### Homogeneous areas of forest

When there is no requirement to develop a map and there is an expectation that strata can be clearly demarked, a multistage sampling approach is highly recommended. There are two commonly used multistage approaches: stratified random sampling and cluster sampling. The number of samples (or clusters) allocated into each stratum can be proportional to the size and variability within the stratum, and inversely proportional to the cost of measurement in the stratum.

This approach to the allocation of samples (called optimal allocation) will provide the best overall precision for a limited measurement budget.

An additional required choice is to define the actual sample element, which can remain as a fixed-area plot (even retaining the original split-plot rectangular design of 0.2 and 0.1 ha) or use a point (also called a variable-radius plot). The point-based designs are highly efficient for determining wood or product volume as they allow, without introducing bias, a concentration of measurement effort on the more valuable trees.

The following approach was developed during an Australian Centre for International Agricultural Research (ACIAR)-sponsored workshop held in Lae in 2003. Let us assume that the total inventory budget would allow about 150 point samples in 50 clusters randomly allocated across the forest of interest. Further, let us assume that reliable maps created by recent remote sensing identified two strata ($S_1$ = 9,000 ha, $S_2$ = 12,000 ha), where $S_1$ was expected to be a little more variable but significantly more expensive to measure than $S_2$. A common measure of variability is the coefficient of variation (*CV%*), defined as 100 × standard deviation / mean. The variation between clusters in a homogeneous stratum would be less than the variation between individual plots/points. Let us assume the *CV%* was 40% and 30% for $S_1$ and $S_2$ respectively.

We do not need to know the exact cost of establishing a plot in order to use optimal allocation, so let us just assume that the costs for the strata were in the ratio 2:1.

### *Determine number of clusters in each stratum*

The optimal allocation formula proportions the number of samples into each stratum using a formula (equation (1)) based on best guesses of the overall size, variation and cost.

$$n_i = c \times \frac{\frac{a_i \times CV\%_i}{\sqrt{c_i}}}{\sum_{i=1}^{n} \frac{a_i \times CV\%_i}{\sqrt{c_i}}} \qquad (1)$$

where:

| | |
|---|---|
| $n_i$ denotes | the number of clusters in stratum *i* |
| $c$ | the total number of clusters that can be established |
| $a_i$ | the area of stratum *i* |
| $CV\%_i$ | the estimated CV% in stratum *i* |
| $c_i$ | the estimated relative cost of establishing a cluster in stratum *i*. |

In the example above, the optimal allocation would be to establish 21 clusters in stratum 1 (expensive but variable) and 29 in stratum 2 (cheaper and more area covered). If the estimates of the *CV%* are reasonable, the expected sampling error or confidence limits using these allocations could be estimated (equation (2)).

$$E\%_i = \frac{t_{(1-\alpha, ci-1)} \times CV\%_i}{\sqrt{n_i}} \qquad (2)$$

where:

$n_i$ and $CV\%_i$ are as above,

| | |
|---|---|
| $E\%_i$ denotes | the expected sampling error in stratum *i*—the true population mean is within *E%* of the sample estimated mean 1–α of the time |
| $t$ denotes | Student's t-value at α probability and $c_i$–1 degrees of freedom. |

In this case the sampling error for $S_1$ and $S_2$ is 18% and 11% respectively, while the overall error is an area-weighted addition of the two absolute errors.

### *Select cluster location*

Randomly select the number of sample locations identified over the net area of each stratum. This selection should not be biased towards areas of easy access or other subjectively important areas.

Establish a cluster of three basal area sweeps around each of the sample locations. The cluster is a triangle with sweeps at each of the corners and 100-m line-transects joining each sweep sample (Figure 2). Information collected on the 100-m transect between sweep points could include an estimate of the percentage of 'harvestable' area, the presence/absence of rare species, or other management information.

### *Point samples*

Each tree that is identified as in the basal area sweep (an 'IN' tree) is measured for diameter and classified for species, merchantability class/form and other variables of interest. It is expected that only 5–20 trees would be included in any one basal area sweep.

On a subsample of IN trees (say every fourth tree), determine the merchantable volume as accurately as possible. This may mean the use of hypsometers to accurately measure bole height and volume tables. Alternatively, these subsample trees may be felled and very accurately measured if the volume estimates are very important. Other details about the terrain etc. can be collected on the 100-m transect sides between the point samples. In particular, line-intersect sampling can be easily used to quantify coarse woody debris, ground and understorey masses, or stocking.

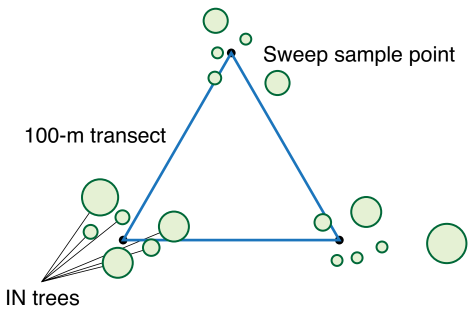



**Figure 2.** Example layout for cluster of point samples

*Advantages of the proposed system for homogeneous areas*

The use of optimal allocation and cluster sampling of points allows for an inventory design that minimises travel costs for the inventory crews, concentrates measurement efforts on the valuable trees, and simultaneously allows the calculation of an unbiased estimate of forest resources. The number of clusters to be established can be determined a priori and in relation to the required degree of precision.

In contrast, a stripline survey covering 1% of the example 21,000 ha would require measurement of an equivalent of over 1,000 plots of 0.2 ha and, unless the striplines are systematically placed over the entire resource, no conclusion on the total precision or estimates can be made. If the striplines were placed systematically (and parallel) across the entire forest, relatively more would be placed in stratum 1 (which is more expensive to measure) than the proportion recommended by equation (1). The sampling error resulting from 1,000 plots (and assuming they are independent, which is not strictly true) would be about 2%, which is substantially smaller than the precision required in any recorded national, regional or even operational forest inventory. If the number of plots established were halved, the sampling error would only increase to less than 3%, which is still much more precise than usually required for good management.

## Using additional information

Although remote sensing data are commonly used to classify images into different homogenous groups, there are often considerably more data available for use. For example, the percentage of canopy cover within 'cells'—foliage projected cover (FPC)—is often used to classify land into non-forest (less than 10% cover) and forest. The lands within the forest and non-forest areas can be described as relatively homogeneous in that each hectare within the forest class is 'more similar' to another hectare within that class than it is to a hectare in the non-forest class. However, even within the 'homogeneous' forest class, the canopy cover can vary significantly. Where this variation can be related to the variation in stand volume (or other parameters of interest in the forest), multiphase sampling approaches can be used to improve the precision and even the spatial resolution of the estimates.

Variation in the FPC (derived from satellite data) over subtropical and temperate forests in Queensland and New South Wales explained almost 60% of the variation in total and merchantable volume (Brack et al. 2011). These same data also explained over half the variation in structural diversity, as related to animal and bird populations.

Even poorer correlations between the remotely sensed variable and the variable of interest can lead to improved precision. Hamilton and Brack (1999) and Brack (2004) demonstrated that using even poorly correlated data collected from remote sensing can lead to sampling errors for total volume that were only one-quarter as large for a given ground sampling effort as those that did not use the auxiliary data.

*Multiphase sampling*

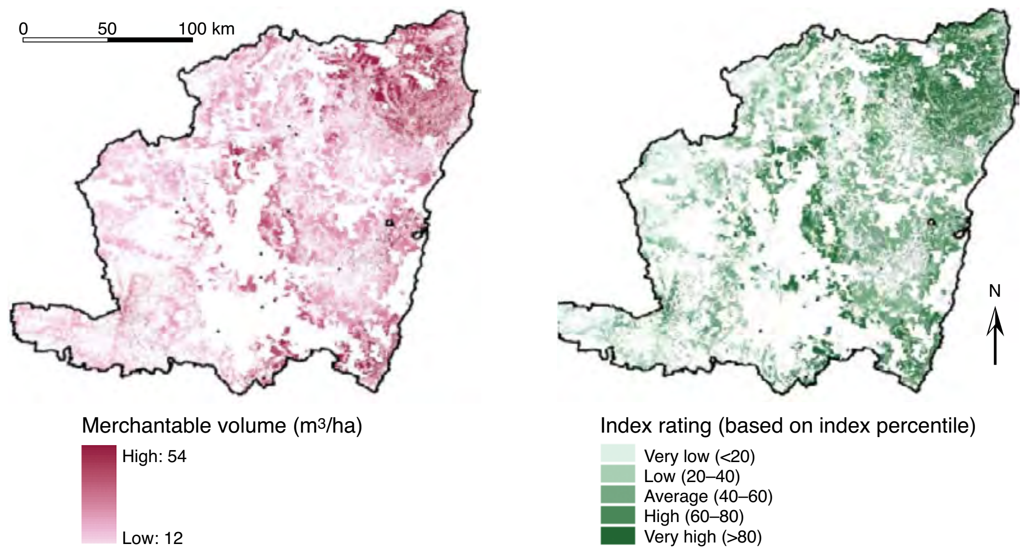
Three common multiphase sampling approaches are ratio, average ratio and regression sampling. Selection of the appropriate approach depends on the consistency of the relationship between the auxiliary variable and the value of true interest, and whether that relationship goes through the origin (Schreuder et al. 1992a). These approaches can be further subdivided into situations where the auxiliary variable is available over the entire area (wall-to-wall) or only in a relatively large subset (systematically or randomly selected). The wall-to-wall variation allows the creation of full cover maps, while the subset option, often called double sampling, provides only improved precision in the estimation of means and totals. Such multiphase approaches are increasingly common for large-scale inventories (Williams 2001) and national inventories (McRoberts and Tomppo 2007).

The multiphase approaches require quantification of the relationship between the on-ground measured parameters of interest and the remotely sensed data. The remotely sensed data are normally based on signals or returns from a pixel or cell and, ideally, the ground-based information should relate to the same-sized cell. For example, the auxiliary variable used for Queensland forests in Brack et al. (2011)—FPC—was derived from satellite images with a cell size of 400 × 600 m. The ground-based information was collected using a cluster of point samples over this 400 × 600 m area.

In Brack et al. (2011) the locations for the ground samples used to quantify the relationship were chosen from an ordered list of FPC, so pairs of FPC and ground data from low to high FPC were collected (Figure 3). A national inventory for forest carbon in New Zealand uses a systematic approach and collects ground data on forests at the intersection of a 20 × 20 km grid to correlate with their remotely sensed data. Ford et al. (2008) and the National Carbon Accounting System (NCAS) for Australia (Brack et al. 2006), on the other hand, did not specifically go out to collect additional ground data, instead relying on pre-existing ground measurements whenever these met quality-assurance standards for measurement practice.

## Discussion and conclusion

Point sampling is commonly used to focus measurement efforts on the trees that contribute most to the biomass, volume and product value of the forest. Schreuder et al. (1992b), for example, compared angle count sampling with fixed-radius plot sampling and found that angle count sampling was most efficient in describing stems/ha, average $d^2h$ (which is an approximation for mean tree volume where d = diameter and h = height) and sum of $d^2h$ (as an approximation of volume/ha by diameter class). Clusters of point samples are therefore appropriate when either stratified random sampling (i.e. into homogenous areas of forest) or multiphase sampling (i.e. quantifying correlations between auxiliary and main interest variables). The placement of the clusters in stratified sampling can be optimised to gain the best precision of the tree volume and biomass per dollar of cost by using equation (1), but the actual location needs to be randomly or systematically (not subjectively) determined. Systematic sampling covering the range of auxiliary variables in a multiphase approach would also ensure the best precision for a given number of sample locations.




a) Merchantable volume ($m^3$/ha)— a regression against FPC, FPI and $FPI^2$ ($R^2$ = 0.59; $n$=16; $p$<0.0028)

b) Stand structural diversity— a regression against FPI and $FPI^2$ ($R^2$ = 0.49; $n$=16; $p$<0.0054)

**Figure 3.** Maps produced by multiphase approach—field data collected from clusters of point samples. Auxiliary data included foliage projected cover (FPC) and forest productivity indexes (FPI). Source: Brack et al. (2011).

Fixed-area plots are more commonly associated with the determination of biodiversity. Motz et al. (2010) continue to recommend fixed-area plots for the calculation of many indexes of biodiversity, but also concludes that '[biodiversity] measures related to basal area [BA], i.e. basal area per hectare and the BA-related Shannon and Simpson indexes, are more efficiently estimated using angle count sampling'. Thus, the use of point samples does not negate the value of the inventory for estimating values other than those associated with tree volume.

However, as point samples do not cover any fixed area, no simple calculation of the relative area sampled using point samples can be determined; therefore, point samples cannot meet the 1% intensity of sampling as currently outlined in the Forestry Act 1991. However, the effective area of a point sample can be determined for a given DBH and basal area factor (BAF) used in the point sample. For example, if the BAF = 2, a 100-cm DBH tree would be IN a point sample if it were within 35 m (equation (3) of the selected point, and thus this point sample covers about 0.38 ha for 100-cm DBH trees.

$$L = 50 \times \frac{DBH}{\sqrt{BAF}} \qquad (3)$$

So, just as the current stripline approach uses two plots sizes (0.1 and 0.2 ha for non-commercial and commercial species respectively), a point sample could be defined as having at least 0.38 ha for the largest DBH trees while going out only 3.5 m for the smallest trees (DBH of 10 cm). Despite this potential to determine area, it is still not efficient to attempt to sample 1% of forest area simply to obtain precise estimates of the mean values. Measurement resources must be more effectively used by collecting higher resolution remotely sensed data or improving the allometrics to predict parameters of interest from DBH and height measurements.

As remote sensing data become more readily available, the move to multiphase sampling that exploits these data is more common. Early examples of multiphase sampling were focused on traditional wood products. More recently, examples that estimate a range of non-wood goods, from biomass and carbon to biodiversity, have become more common. The auxiliary data used in these approaches include more than the direct information from the sensors, and the NCAS is a good example where the remotely sensed data it integrated with climate and soil data, through time, were used to generate maps of forest productivity and disturbance history. Brack (2007) claims that 'It is difficult to conceive of any parameter of national interest that is not at least weakly related to one or more of these available auxiliary variables [disturbance or productivity]'. Where the auxiliary data are available over wall-to-wall, the multiphase approaches also allow the creation of detailed maps that include estimates of precision for quantitative predictions at any point. Such maps are generally far superior to those created by striplines unless the distance between the striplines is prohibitively small.

Given the current legal requirement for a 1% inventory and the increasing scrutiny of legality for both large- and small-scale forest operations, it is recommended that the current legislation be amended to provide greater flexibility in the specification forest inventory, based on measures such as desired accuracy, that will allow the use of the more-efficient sampling approaches described in this paper.

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# The information content of synthetic aperture radar imagery of tropical forests

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*Abstract*

Synthetic aperture radar (SAR) systems, whether airborne or spaceborne, can be characterised by their frequency, bandwidth or resolution, imaging geometry, polarimetry and interferometric capability. Each characteristic plays an important role in determining the information content of SAR imagery of tropical forests. For example, at high-frequency (X-band) SAR imagery, absorption is high, scattering arises predominantly from smaller objects such as leaves and twigs, and shadowing by vegetation canopies influences texture. At low frequency (P-band), absorption is low, scattering arises mostly from larger plant structures, and the ground–stem interaction is important—vegetation biomass, ground moisture and slope influence the properties of the imagery. Enhancing resolution and adding polarimetric and interferometric capability yields additional information that can also be exploited. Because SAR observation is not hampered by cloud cover, the role of SAR in the tropics is an important one. Papua New Guinea is fortunate in having available extensive SAR data at X-, L- and P-bands, with interferometric data at X- and P-bands. The data available provide a wealth of information, and this paper discusses both the nature of this information and the means by which it may be extracted.

## Introduction

The monitoring and protection of tropical forests is an essential part of the international effort to curb greenhouse gas emissions. Deforestation and degradation of tropical forests, which contain ~40% of the world's plant carbon (C), are thought to account for ~20% of the world's anthropogenic carbon dioxide emissions (Dixon et al. 1994). Remote sensing has an important role to play in the Reduced Emissions from Deforestation and Degradation (REDD+) initiative of the United Nations Framework Convention on Climate Change (UNFCCC 2007). A multisensor approach to measurement, reporting and verification (MRV) activity is most likely, and a review of what each different technology has to offer in this regard may be found in Williams and Jenkins (2009).

Cloud cover is an important issue in the tropics as it prevents optical sensors from observing the forest, and this can present a severe problem for MRV. For example, in the wet season the probability of obtaining LANDSAT imagery of the Amazon rainforest with less than 30% cloud cover is typically below 20% (Asner 2001). Radar has the ability to penetrate clouds, and synthetic aperture radar (SAR) observation of rain forests is not hampered by cloud cover (although heavy rainfall can affect X-band observations).

Interest in the potential of SAR to provide unhindered monitoring of tropical forests began in the 1990s with the launch of the spaceborne C-band SAR systems ERS-1 (1992) and ERS-2 (1995), Radarsat I (1995) and the L-band JERS-1 (1992). It has gathered pace with the advent of polarimetric SAR systems such as the L-band ALOS PALSAR (2006), C-band Radarsat II (2007) and, most recently, the X-band systems TerraSAR-X (2007) and Tandem-X (2010).

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Early SAR satellites were high-frequency, short-wavelength systems, operating at C-band (5–6 cm wavelength). The band nomenclature dates back to World War II and was intended to be obscure for security purposes. Radar backscatter (the amount of energy reflected back to the radar) at short wavelengths (e.g. X-band, which is around 3 cm) arises predominantly from the upper forest canopy, from leaves and twigs and the smaller plant elements (Le Toan et al. 1992). These scatter strongly as they have dimensions similar to the wavelength. The moist canopy quickly absorbs any forward scattered energy. At such wavelengths there is often little difference in backscatter brightness levels from differing types of vegetation. However, texture in short-wavelength SAR images is influenced by canopy topography (Williams 1997), the effects of which have been exploited to differentiate forest and clearing from short wavelength SAR imagery of tropical forests (Oliver 1998; Grover et al. 1999).

L-band wavelengths are of the order of 24 cm. At these wavelengths less energy is absorbed by the small plant elements, which also scatter less energy as a result of their reduced size relative to the wavelength. Thus, more energy penetrates to the lower canopy, and larger tree structures affect the radar backscatter more strongly. At L-band, backscatter from the ground can appear reduced compared with that at shorter wavelengths, and the contrast between forest and clearing may be increased. At the same time, energy can be scattered from the ground forward onto the trunks and primary branches, from where it is scattered back to the radar. This ground–volume (direct reflections from the forest canopy) interaction becomes significant as the wavelength increases to L-band (Leckie and Ranson 1998).

Leaves, twigs and smaller branches attenuate microwave radiation both at L-band and lower frequency P-band, with typical wavelengths of around 90 cm (Kasischke et al. 1997). However, the progression is not regular, and P-band has been observed to penetrate markedly further than L-band (Hensley 2003). The ground–volume interaction at P-band is also enhanced over that at L-band, and can come to dominate the backscatter returns over the volume components. At the same time, direct returns from the soil or grassy areas are greatly reduced and forest/clearing differentiation is clear. The strong ground–trunk interaction, and that between large primary branches and the ground, can yield very bright, narrowly focused returns that enhance the texture of forest imagery at P-band.

For the interested reader who wishes to investigate these effects, a software simulation (PolSARproSim) is available from the European Space Agency website as a free download. The software permits the user to simulate forests stands and calculates SAR images of the forests at L-band and P-band wavelengths. The simulation is part of the educational software tool set PolSARpro (http://earth.esa.int/polsarpro/). This tool set includes valuable tutorial information on SAR, in particular on polarimetric SAR, and would serve as a suitable accompaniment to this article (Pottier et al. 2008). Another excellent resource is the book ‘Understanding synthetic aperture radar images’ (Oliver and Quegan 1998).

At P-band, and to a lesser extent L-band, backscatter arises from the large primary branches and trunks or stems, and the volumes of these elements influence the amount of backscattered energy. There is therefore a link between brightness levels in low-frequency SAR imagery of forests and forest biomass. However, this link is far from simple—tree architecture (the angle and distribution of branches) can also affect backscatter, and the competition between attenuation and scattering in the canopy leads to saturation of backscatter at high biomass (Le Toan et al. 1992; Hoekman and Quinones 2000). The biomass of a tree may also be linked to its height through allometry (Chave et al. 2005). SAR interferometry can also be used to estimate the forest height, providing another link to biomass (Neeff et al. 2003; Williams et al. 2009). Imaging geometry (incidence angle), resolution and polarisation also affect the information content of SAR forest observations.

Papua New Guinea (PNG) is doubly fortunate in that it has a large area of primary forest that is home to one of the most diverse ecosystems in the world, and because SAR data are available over the full range of wavelengths discussed in this introduction. In 2006 PNG was mapped using the GeoSAR airborne system (Wheeler and Hensley 2000), which collected high-resolution interferometric SAR data at X-band and P-band over the mainland. X-band interferometric data were also collected over the islands using Intermap’s Star-3i system. ALOS PALSAR has collected L-band polarimetric data over PNG, and mosaiced datasets are available for 2007 and 2008. ALOS PALSAR, Radarsat II (C-band, polarimetric data) and the new, fully polarimetric X-band satellite TerraSAR-X systems are currently operational and collecting data over PNG’s forests.

In this paper a small set of these observations (GeoSAR and PALSAR) is used to illustrate the nature of the information content of SAR imagery of forests in PNG. The physical scattering processes that result in information being encoded in X-band, L-band and P-band SAR imagery, and the nature of that information, are explained.

The interpretation of SAR imagery has, in the past, been hampered by its statistical nature. SAR images contain speckle that results from the coherent (phase-preserving) imaging process, which tends to yield 'grainy' imagery that requires greater effort in interpretation than optical imagery. In recent years the transition from raw SAR data to useful geospatial information has evolved considerably, and a wide range of techniques is now available to facilitate the transformation process. The process of information retrieval from SAR imagery is illustrated with an example of land-cover classification using GeoSAR data over a large area in PNG.

## Information in X-band SAR imagery of forests

Information about land-cover classes can be encoded in high-frequency, high-resolution SAR imagery through the interaction of vegetation canopy topography, scattering physics and imaging geometry. Although different vegetation classes have similar brightness at X-band, the information is carried in texture in high-frequency SAR imagery (Williams 1997; Oliver 1998; Grover et al. 1999).

An example of X-band imagery from PNG is shown in Figure 1. There are three distinct land-cover types in the SAR image. In the top centre of Figure 1(a) there is a relatively smooth region of rubber plantation. To the south of this is a large grassy clearing with the occasional tree and large bush. Other, smaller clearings are also visible, and in all clearings the SAR imagery displays a relatively smooth texture. Elsewhere, there is forest, which displays a rough texture.

In Figure 1(b), a calculation of a texture measure is displayed that depends upon the variance of the pixel intensity in image regions calculated using eCognition segmentation software. Light values indicate a larger variance and dark values a lower variance. There is a distinct difference between texture over clearings and plantations, and texture over the forest. This difference was exploited in C-band imagery from the spaceborne ERS1 SAR to indicate deforestation in the Tapajos region of the Brazilian Amazon (Oliver 1998; Grover et al. 1999).

To understand why this should be the case, it is necessary to consider the way in which SAR images are formed, beginning by considering the distribution of pixel values in the cleared grassy area. Why does the image appear so 'noisy'?

In fact, this particular noise is not noise at all, but 'speckle', and the distribution of pixel values in speckle is understood. Speckle arises because SAR is a coherent imaging sensor— that is, signal phase information is preserved, and indeed is necessary for image formation. Resolution of the SAR image in Figure 1a is fine—around 1.25 m—and

(a) (b)

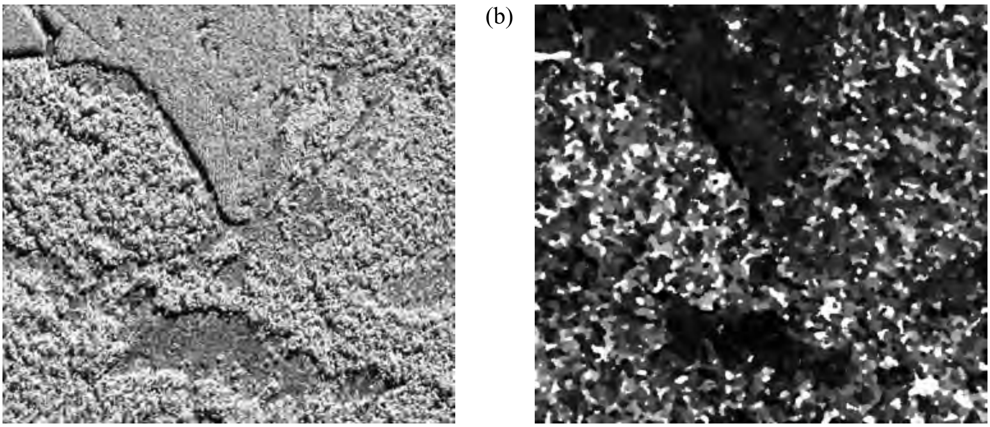


**Figure 1.** (a) High-resolution X-band imagery of forest, rubber plantation and clearing in Papua New Guinea; and (b) a measure revealing the different textural properties of the image for the different land-cover types

the wavelength at X-band is around 3 cm, so pixels are approximately 40 wavelengths square. Thus, the phase of the returning signal can pass through a complete cycle many times across a single pixel.

In any pixel area there are many discrete scattering objects— for example leaves, twigs or blades of grass. Each object scatters the radar energy back to the SAR, and each scattered wave carries phase information that is different from that of the wave of the neighbouring object.

The scattered radar waves are added coherently by the SAR sensor for each pixel. Those with the same phase add constructively, while those with large phase differences add destructively. Thus, the total received signal for the pixel is variably large or small depending on the number of discrete scattering objects, their ability to scatter radar energy and their spatial distribution within the pixel. So, sometimes there are bright pixels and sometimes dark pixels, even if the amount of vegetation, or rough surface, is the same for each pixel—SAR senses the distribution of material in space. This is one of the reasons that land-cover classification is complicated when using SAR imagery—even though the land cover may not change from pixel to pixel, neighbouring pixels may have very different brightness values. Successful retrieval of information from SAR imagery requires a strategy to deal with this situation, and one example is described later in this paper.

When the number of 'effective scattering centres' (e.g. the number of leaves or blades of grass in this example) is large, the distribution of pixel intensity values is exponential (Oliver and Quegan 1998). For an exponential distribution the ratio of the mean squared intensity to the square of the mean intensity (related to the variance of the intensity) has the value 2. In the clearing region in the X-band image of Figure 1, the pixel distribution has a value close to this, as reflected in the texture image where the area appears relatively dark.

The forested area in the X-band image of Figure 1 displays a greater intensity variance than the grass clearing. To understand this, consider that the last 'r' in 'radar' stands for 'ranging'. Radars see things (for each single azimuth direction) at the same location if they have the same range, and SARs are no different from other radar systems in this regard. Also, brightness in the image depends upon the local incidence angle of the wave at the forest canopy, and the canopy attenuates incident radiation. Combining these facts with the explanation of speckle yields a model of 'clutter' that explains the enhanced variance in the distribution of pixel intensity (brightness) values over the forested area.

Consider the SAR imaging of the two forest canopies shown in Figure 2. The closed forest canopy (green) can be considered as a collection of small scattering objects (leaves and twigs). The blue lines approximate lines of constant slant-range, and the gap between the lines is the width of a pixel. On the left the canopy height is quite uniform and the mean pixel brightness is the same for all pixels (range gate A). On the right the crowns are emergent and the situation is complicated. On the edge of the crown closest to the radar (range gate B) the scattering is very strong since the local incidence angle is small, and geometry ensures that a single range gate (pixel) collects the backscatter from a large surface area of brightly scattering objects. The brightness from trailing edges of tree crowns becomes progressively lower (darker pixels) moving away from the leading crown edge. The local incidence angle increases and the area over which the scattered radar energy is collected becomes smaller, and eventually the trailing crown surface enters strongly shadowed areas due to canopy attenuation (range gate C).

Leading crown-edge pixels are extremely bright, and this is clear in the imagery of Figure 1(a) at the edges of forested areas. In Figure 1 the radar is viewing the scene from the north-east. Crown shadows are also evident in the forest area. Note that the mean pixel brightness is just the mean of the local exponential intensity distribution, and pixel values are still distributed. Not only do leading-edge pixels become bright, but there are also fewer of them than the darker, trailing-edge pixels. The mean pixel brightness in X-band SAR imagery varies across the forest canopy surface when tree crowns are emergent. This variation affects the distribution of pixel intensity values and increases the pixel intensity variance. This increase is displayed in the texture image in Figure 1(b).

SAR resolution is important. If the pixels were so large that many tree crowns were to be found in a single pixel, the mean pixel brightness would again be spatially uniform, and the intensity distribution would again appear to be exponential (instead of *K*-distributed, see, e.g., Oliver and Quegan 1998). This has generally been the case for low-resolution satellite imagery, although now TerraSAR-X (http://www.infoterra.de/terrasar-x-satellite) can achieve resolutions approaching those of Figure 1(a).

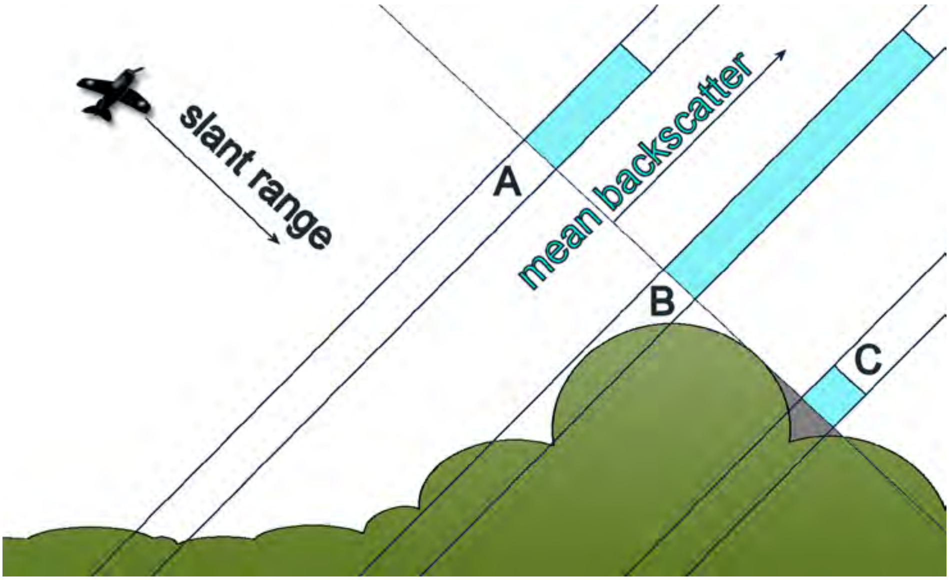



**Figure 2.** Forest canopies with different canopy topographies can yield different pixel intensity distributions when imaged by the same high-frequency SAR. On the left the canopy is of uniform height, while on the right the tree crowns are emergent. The cyan scale indicates the mean pixel brightness for pixels at that range.

The global incidence angle is also important. When it is low, shadowing is minimal and the change in texture is not significant. However, when it is high, there is more shadowing, affecting the imaging of the upper canopy, and the distribution of pixel intensity values increases (Williams 1997). These effects have important consequences; for example, the Amazon rainforest has been used for antenna pattern calibration for Radarsat systems (http://www.asc-csa.gc.ca/eng/satellites/radarsat2), and it has recently been discovered that incidence angle effects can affect the calibration (Cote et al. 2009).

The GeoSAR data used in the Figure 1 have a resolution of 1.25 m, which is usually substantially less than the diameter of the emergent crowns of tall tropical forest trees. Thus, the effects of texture change quite clearly. The texture over the rubber plantation is not enhanced because the trees in the plantation were planted at the same time and have grown at the same rate. The rubber plantation canopy is therefore relatively uniform in height compared with the forest, and shading and shadowing effects are negligible. This is why the texture in the rubber plantation appears similar to that of the grassy clearing, even though the rubber plantation is mostly brighter than the clearing.

## Information in P-band SAR imagery of forests

When the physics of scattering changes as a result of the change in wavelength, so does the way in which information is encoded in SAR data. While high-frequency satellite SAR systems are now almost commonplace, there is no commercial satellite for P-band SAR, although studies for such are currently being undertaken by the European Space Agency. There are several good reasons why this should be the case. The bandwidth available to yield good resolution is limited at P-band, focusing of a P-band SAR is not as simple as it is for an X-band SAR, and the effects of the ionosphere on the polarisation of P-band waves are significant and variable. So, despite the fact that both physics-based modeling (Hsu et al. 1994; Williams 2006) and airborne P-band SAR observation (Le Toan et al. 1992; Neeff et al. 2003; de Souza Soler and Sant'Anna 2007; Dubois-Fernandez 2007; Williams et al. 2009, 2010) have demonstrated the strong link between tropical forest parameters and P-band SAR observations, the availability of P-band data is somewhat limited.

Whereas scattering at X-band arises from the upper canopy, P-band scattering over forests can be modelled accurately using a combination of three scattering mechanisms. These are the direct-ground return (scattering by rough, wet ground surfaces), the direct-volume return (direct scattering by the primary branches and stems) and ground-volume scattering (scattering of the forward reflected wave by stem and branches). The last is illustrated in Figure 3. For HH polarisations (polarisation effects are discussed in the following sections) the ground-volume term can be the most significant, while for HV polarisations the direct-volume returns are generally dominant.

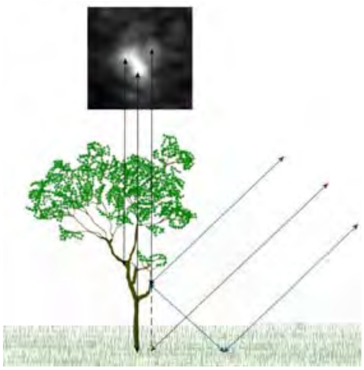
The ground-volume interaction is interesting for a number of reasons. First, the strength of the wave scattered by the ground depends upon the ground roughness and moisture content—wetter surfaces are more reflective, while rougher surfaces reflect more energy back to the radar and less is scattered forward. The ground-reflected wave is then scattered by the primary branches and trunk, and the strength of the wave scattered back to the sensor depends upon the shape, orientation, dimensions, volume and water content of the tree. So the ground-volume scattering term carries mixed information about the ground and the forest.

The strength of ground-volume scattering depends also on the slope of the terrain in both range (radar look) and azimuth (orthogonal) directions. A tilt in azimuth changes the angle between the polarisation vector and the ground, which affects the return since the ground reflects polarisations differentially in the forward direction (as anyone with polarising sunglasses can confirm). A ground tilt in the range direction generally implies a change in angle between the stem and the ground, since stems remain predominantly vertical on sloping terrain. This changes the bi-static angle for stem scattering of the ground-reflected wave, which alters the strength of the backscatter. This effect can be dramatic above 10° or so of slope. Since P-band HH returns also comprise direct-volume returns, terrain slope changes alter the ratio of direct-volume to ground-volume scattering, which in turn has implications for P-band interferometry (Lavalle et al. 2009).

However, it is the geometrical properties of the ground-volume interaction (Lucas et al. 2006) that are perhaps the most dramatic, at least when the terrain is level and horizontal. These are revealed in the dramatic texture of the P-band HH image of Figure 3, wherein individual coconut trees can be recognised in a plantation at Hisiu in PNG.

The diagram in Figure 3 attempts to illustrate the fact that, for each ground-volume scattering path (blue), there is an equivalent direct path (red). This direct path equivalent range makes the radar 'see' the ground-volume scattering from a tree element as arising from the ground directly below the tree. This effect makes all the ground-volume scattered energy from tall, straight stems focus in the SAR image at the same location, making the stem response stand out as a well-focused bright point when the ground is level and horizontal. This effect is illustrated in the coconut plantation image, wherein it is possible to count the stems of the widely separated coconut trees.

Why then do P-band images of forests not show the individual trees in the forest? The answer lies in the canopy and the effects of attenuation, which can be seen even at P-band. The images in Figure 4 show an area that contains rubber plantations of different



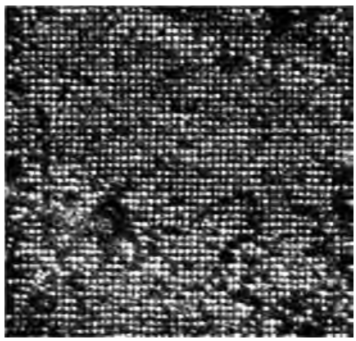


**Figure 3.** The geometry of ground-volume SAR interactions at P-band (left) and a high-resolution GeoSAR P-band (HH) image of the coconut plantation at Hisiu, Papua New Guinea (right)

ages separated by a road running darkly and diagonally across the image. North of the road the rubber plants are young and thin and the canopy is light. South of the road the plants are older, the stems are thicker and the canopy is denser. In the image of the young rubber plantation the (bifurcating) tree stems are almost distinguishable to the extent that a tree count could be estimated from the image. By contrast, in the image of the mature plantation the texture is unbroken except by gaps in the cover, and individual trees are not readily discerned.

The reason for the marked difference in texture is to be found in the effects of attenuation. The thicker canopy of the mature rubber plantation attenuates the incident radiation more severely than the canopy of the young plantation. As a result, direct-volume backscatter in the mature canopy is enhanced over ground-volume scatter, since the full depth of the canopy must be traversed twice for the latter, incurring maximum attenuation, while the scattering path is only a fraction of the full canopy depth for direct-volume scatter. This delicate balance between attenuation and scattering strength is typical of the situation in low-frequency observation of forests. As a result of the preferential attenuation of ground-volume returns, which are also affected by terrain, the well-focused ground-stem images are hidden among the more diffuse direct volume contributions, and the texture is altered.

The preferential attenuation of ground-volume and direct-ground interactions by mature forest canopies has another effect. Interferometric SAR systems use two separated antennae (or one antenna twice) to measure height. The radar sees the ground-volume interaction in forests, as with the direct-ground interaction, as coming directly from ground height (see previous discussion). Thus, if the ground-volume and/or the direct-ground interaction is strong at P-band for forests, the interferometric height is close to the ground height below the trees, and P-band SAR interferometry yields a true digital elevation model (DEM). However, direct-volume scatterers have heights distributed above the ground, and SAR interferometry for direct-volume scattering yields heights above the ground. Both direct- and ground-volume contributions are present in any P-band interferometric signal of forest. As the direct-volume term increases in strength over the ground-volume and direct-ground terms, so the recovered interferometric height rises ever further above the ground (Figure 5). So, as the ground becomes dry or rough, or the canopy becomes denser, or terrain slope increases, the contribution to total P-band forest backscatter of ground-volume terms decreases. These changes can be detected in SAR magnitude imagery and interferometric data. An examination of the DEM height for the rubber plantation in this example reveals that the height recovered below the mature rubber trees is significantly higher than that recovered below the young rubber trees.

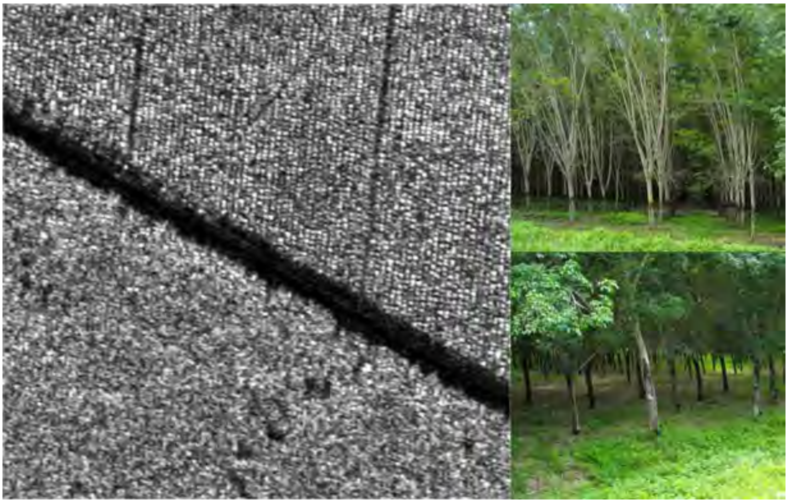


**Figure 4.** P-band image of rubber plantations showing a difference in texture between young (upper) and mature (lower) plantations

(a) (b)

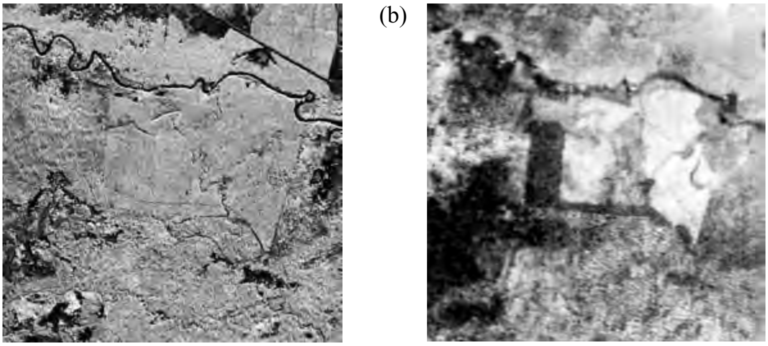


**Figure 5.** (a) GeoSAR P-band HH magnitude image of central rubber plantation distinguished by smoother texture, and (b) the P-band HH DEM for the same area, revealing that the interferometric DEM height recovered from the mature plantation area is raised (lighter grey) with respect to that recovered from the young plantation areas (see preceding text for explanation). The region north of the road is at a higher elevation.

## Information in L-band SAR imagery of forests

Microwave radar backscatter from forests at L-band (~24 cm wavelength) is a more complicated mix of scattering mechanisms than at X-band or at P-band. It is common that, at L-band SAR observation of forests, no single scattering mechanism (direct-ground, direct-volume or ground-volume) may be dominant. Volume scattering from secondary branches is significant at L-band, especially when transmitting horizontally polarised and receiving vertically polarised waves. Polarisation here means the direction of oscillation of the electric field vector of the radiation, and vertical and horizontal directions are orthogonal. The directions are specified with respect to the transmitting antenna, but horizontal can essentially mean parallel to the locally flat earth.

As has been mentioned, there is competition in the canopy between scattering and attenuation. The more material in the forest canopy, the more there is to scatter back radar energy to the sensor, but there is also more water to absorb radar energy. At low biomass, scattering wins over attenuation; however, as the biomass of the forest increases, so does the backscatter level, and direct-volume returns start to win out over ground-volume and direct-ground returns. At some point the competition between scattering and attenuation is over, and the backscatter saturates and may even decrease slightly—the forest biomass may increase but the radar brightness does not change further. This happens very early for X-band, at around 150 tonnes per hectare (t/ha) for P-band, and about 50 t/ha for L-band.

For L-band at low incidence angles, the horizontally polarised and received (HH) and vertically polarised and received (VV) returns are similar, and the backscatter returns from direct-ground scattering can be commensurate with the biomass saturation level of direct-volume scattering. This makes recovery of forest biomass at L-band less straightforward than at lower frequencies such as P-band, especially as the direct-ground return is further complicated by its dependence on surface roughness and moisture content. At intermediate incidence angles, the ground-volume return is present but not nearly as significant as it is at P-band. L-band interferometric heights over tropical forest have been observed that are not significantly lower than those obtained at X-band, indicating that attenuation at L-band is much greater than it is at P-band (Hensley 2003).

The horizontally polarised and vertically received (HV) return is governed predominantly by volume scattering from the forest crown. Although the ground can influence the HV returns to some extent, the connection between HV polarisation backscatter and crown volume can be used to help map forest cover. When the forest crown is absent, the HV returns are very low since direct-ground returns at HV are generally an order of magnitude below HH and HV returns for bare soil or grassy ground. For a random canopy, one expects the HV returns to be a sizeable fraction of the HH returns. Thus, the HV:HH ratio (or the (HH–HV):(HH+HV) ratio, or similar) can be used as a forest indicator. The ratio is generally largest for high-biomass forest and very low when forest is absent.

Use of the dependence of HV and HH backscatter at L-band on forest cover is illustrated in Figure 6. The image is a false-colour composite formed from ALOS PALSAR 50 m mosaic data of PNG showing Port Moresby and surrounding areas. In the image, HV backscatter is shown in green, and HH in red and blue. Thus, the greener the colour, the greater the vegetation (forest) cover, and the redder or more purple the colour, the less HV and therefore the less forest. The data are from 2007, and no correction has been applied for terrain slope. There is a very strong signal that an area to the east of Port Moresby has been cleared, presumably in preparation for a new plantation.

Just as HV is linked strongly to direct-volume backscatter, so HH and VV may be connected with (at different incidence angles) direct-ground (low incidence) and ground-volume (intermediate incidence) scattering. As discussed in the previous section, ground-volume backscatter appears to the radar to originate on the ground. Direct-ground backscatter clearly appears to the radar to originate at the ground but has a different polarisation signature when the polarisation phase between HH and VV is compared. The relationship between polarisation and scattering mechanisms has been recognised and exploited. If SAR interferometry is attempted with a polarimetric SAR, the amount of available information increases dramatically.

For example, when performing HH-HH polarimetric interferometry with both the interferometric antennae set to transmit and receive horizontally, the interferometric height is expected to be closer to the ground at L-band, and to a greater extent at P-band. On the other hand, if both antennae transmit horizontally and receive vertically, the HV-HV interferometry should have a height in the canopy.

The technique is known colloquially as PolInSAR, i.e. polarimetric interferometric SAR (Cloude and Papathanassiou 1998) and can be used to recover estimates of forest height. This has even been undertaken for tropical forests at L-band but only for low biomass (Hajnsek et al. 2009). Since tree height and biomass are linked (e.g. Chave et al. 2005), the technique promises to permit extension of L-band biomass recovery to higher biomass values (e.g. up to the P-band backscatter-only saturation limit of ~150 t/ha). The combination of interferometry and radiometry at both X-band and P-band has been used to recover tropical forest biomass (Neeff et al. 2003; Williams et al. 2009, 2010), and this technique seems to extend the recoverable biomass range significantly beyond this limit.

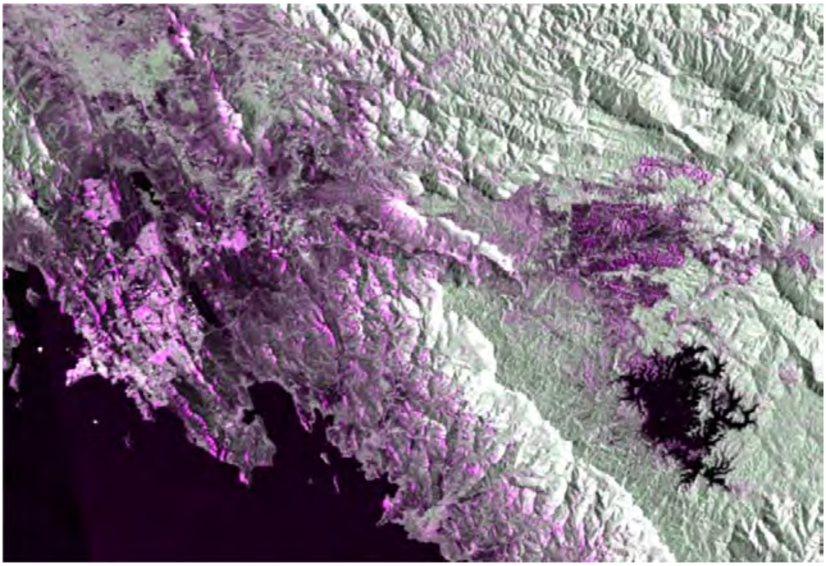


**Figure 6.** L-band (HH (red), HV (green), HH (blue)) 50 m resolution PALSAR data of Papua New Guinea. The false colour composite reveals un- and deforested areas since L-band HV scattering is strongly associated with canopy-volume backscattering.

## Extracting information: land cover classification

Classification of land cover in tropical regions using radar images has proven to have its own advantages over classification based on optical imagery, mainly because of cloud-cover penetration capabilities and better temporal resolution than cloud-free mosaiced products in the optical range. The following example is a land-cover classification based on GeoSAR data using both X-band and P-band collected simultaneously over PNG in 2006. The combination of high-resolution P-band and X-band SAR images (1.25 m resolution orthorectified images) can accurately distinguish not only forest cover from non-forest, but also different types of forest by species composition and stage of growth.

The GeoSAR system is a unique airborne sensor with the capability of collecting interferometric data at high resolution, both X-band and P-band, from both sides of the aircraft, and is therefore a very useful mapping instrument (Wheeler and Hensley 2000). P-band interferometry is performed using only horizontal polarisation, while X-band uses only vertical polarisation. Nevertheless, the combination of data at both high- and low-frequency bands is as useful as fully polarimetric data collected at a single frequency (such as L-band) because of the diversity of information encoded in the SAR imagery.

As has been seen, pixel values in SAR imagery are distributed and, in order to get good estimates of the underlying mean pixel value, need to be averaged. The only option with final data products is to average spatially, which reduces spatial resolution, so there is a trade-off between information accuracy and resolution. The better the resolution, the more accurate the information will be at any particular spatial scale.

When averaging spatially, it is important not to average across the boundaries between different land-cover classes as this introduces inaccuracies into the information retrieval process. In order to preserve image boundaries and still recover areas for spatial averaging, image segmentation should be chosen as one of the post-processing stages. Image segmentation methods are discussed in Oliver and Quegan (1998), and essentially can be used to divide images into regions that are statistically homogeneous—displaying pixel values originating from a single distribution and having a common mean value. This permits the statistical measures recovered from the regions to be meaningful.

Before segmentation, however, there is at least one other facet of SAR imagery that must be taken into account if the classification is to be successful. The observant reader will have noticed that pixel mean brightness depends upon local incidence angle as much as land cover, and therefore on terrain slope. In the discussion of X-band imagery of forests and texture, the ‘terrain’ was the forest canopy topography, since X-band scattering is dominated by direct returns. At P-band the ground-volume terms are strong and the terrain is close to the true ground surface. In order to interpret changes in mean pixel brightness (or indeed changes in texture) between regions in an SAR image as changes in land cover, the effects of local incidence angle on pixel brightness must first be corrected. By removing the dependence of brightness on terrain slope, we increase the contrast between land-cover classes is increased.

The following supervised classification collected samples for classifier training and validation using information from P-band and X-band magnitude layers, and the corrected X–P height difference layer. In the first example, training and validation areas were chosen for each of six land-cover classes identified for the region in Figure 7. This region, close to the Edevu River in PNG, contains areas of cultivated teak and natural forest. The six land-cover classes delineated in the region are:

- class 1: water, with low to no return from both X- and P-bands
- class 2: mature teak, with brighter return in both bands and a smoother texture due to denser canopy and leaf structure
- class 3: logged teak, with lower return from both bands caused by tree cover thinning and gaps in the canopy
- class 4: short vegetation/grass, with low return from both bands
- class 5: primary forest with bright return in both bands, but rough texture due to taller trees and bigger vertically structured canopies that allow shadowing
- class 6: secondary forest with smoother texture in the magnitude images due to smaller tree crowns and less shadowing, and lower values in the X–P height difference layer.

To ensure accuracy of training areas, geo-referenced ground data collected in October 2010 were employed to aid in the identification of different types of land cover. This is particularly important for SAR imagery since signatures are often ambiguous, even to the experienced observer.

The classification was performed at segment (object-based) level using classification and regression tree (CART) analysis (C4.5 algorithm; Quinlan 1993). The decision tree was built using information from six layers: the P-band DEM, P-band and X-band terrain-corrected magnitude images, terrain-corrected X–P DEM difference, P-band DEM-derived gradient image, and shadowing information. Some of the layers and the resulting classification are shown in Figure 7.

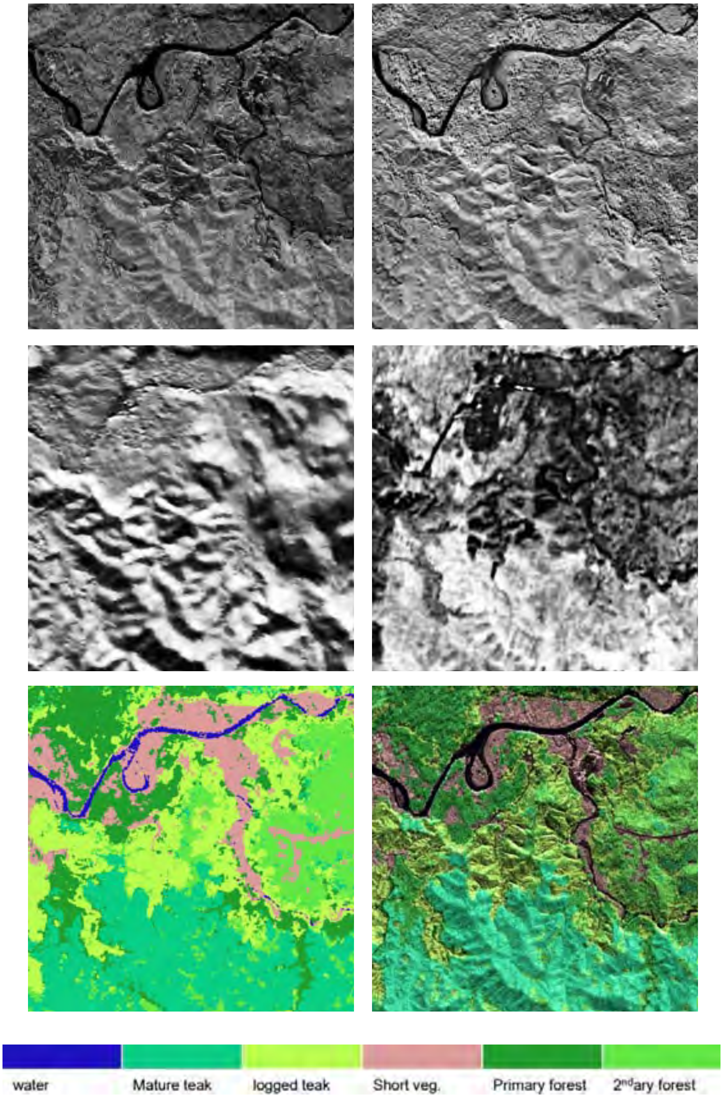



**Figure 7.** GeoSAR data and land-cover classification for a region near Edevu River, Papua New Guinea, collected in 2006, and the land-cover classification obtained using the data. Top left: P-band magnitude; top right: X-band magnitude; middle left: P-band DEM terrain slope map; middle right: difference between X-band and P-band DEM; lower left: colour-coded land-cover classification; and lower right: the same overlaid onto the P-band magnitude image.

The results of the classification are summarised in the confusion matrix in Figure 8. There is an overall accuracy of 93% for the sampled data, with higher accuracies for mature teak and short vegetation (94% and 97% respectively) and lower accuracies for logged teak and secondary forest (90% and 88% respectively). The confusion between logged teak and secondary forest is created by similarities in 'vegetation height' (the X–P DEM corrected height difference) and textures, and occurs in areas where the two classes are adjacent.

The classification uses measures of texture (Haralick et al. 1973) calculated from terrain-corrected magnitude imagery. The combined technique of object-based classification yields a reliable route to the use of SAR imagery for land-cover classification.

Finally, these techniques are being employed on behalf of the Department of Environment and Conservation in PNG to aid in the conservation of the Kokoda Track and Owen Stanley Ranges region. For this study we have employed a similar methodology to classify ~5,000 km2 of the current area of interest. The prediction of classes has been achieved using support vector machine (SVM) technology (Chang and Lin 2001) rather than CART technology, but still at the object level. Object features used as input to the analysis, besides mean and standard deviations for features within segments, include different Haralick texture measurements.

Using these techniques, more than 20 classes have been identified with an overall accuracy of 92% (Figure 9). This means that 92% of validation regions, not used to train the classifier, were assigned their given class by the classifier. Current work is in progress to validate and refine the classifier performance with field sampling. The performance is considered to be good given the size of the area and the variety of terrain—from coastal lowlands to upland hills.

The confusion matrix (Figure 10) can again be used to help understand the nature of the information in SAR imagery. For example, scrub is confused with grass and bare soil around 10% of the time. This is because both classes have low backscatter at P-band, similar backscatter at X-band and similarities in texture. Around 2% of tall mangrove is confused with forest, and this is to be expected given the knowledge of the increase in attenuation for tall forest canopies. Around 3% of primary forest is classified as secondary, as one might expect as secondary forest matures. Primary forest is, however, correctly identified as such over 98% of the time.

In fact, if classes are divided into either forest or non-forest categories, the classification technique described here can correctly identify forest as forest 99% of the time, and non-forest class around 96% of the time. This technique is possible for wide areas and, once the classification scheme has been generated, requires minimum intervention. Region sizes in the classification process are typically less than 1 ha in area and usually much smaller than this. Couple this with the ability of radar to see through cloud cover, which is a severe issue for PNG, and it is clear that SAR has the potential to provide wide-area, high-resolution forest inventory, such as would be required as a component of a REDD+ MRV system.

## Discussion

SAR sensors can be used to encode information about forests over wide areas at regular intervals. SAR is particularly important in the tropics where cloud cover hampers the regular acquisition of optical imagery. It has the added advantage of being sensitive not only to land cover, but also to forest biomass, when low-frequency sensors are used. The encoded information may be accessed and used to derive accurate land-cover classifications at high spatial resolution.

| | water | mature teak | logged teak | short veg | primary forest | secondary forest | | |
|---|---|---|---|---|---|---|---|---|
| water | 150 | | | 1 | | | 151 | 0.99 |
| mature teak | | 852 | 3 | | 26 | 22 | 903 | 0.94 |
| logged teak | | 4 | 715 | 15 | 18 | 39 | 791 | 0.90 |
| short veg | 2 | | 14 | 550 | 1 | 1 | 568 | 0.97 |
| primary forest | | 15 | 22 | 4 | 752 | 19 | 812 | 0.93 |
| secondary forest | | 29 | 45 | 2 | 13 | 632 | 721 | 0.88 |
| | 152 | 900 | 799 | 572 | 810 | 713 | 3946 | |
| | 0.99 | 0.95 | 0.89 | 0.96 | 0.93 | 0.89 | | 0.93 |

**Figure 8.** Confusion matrix for the supervised classification in the teak plantation area of Figure 7

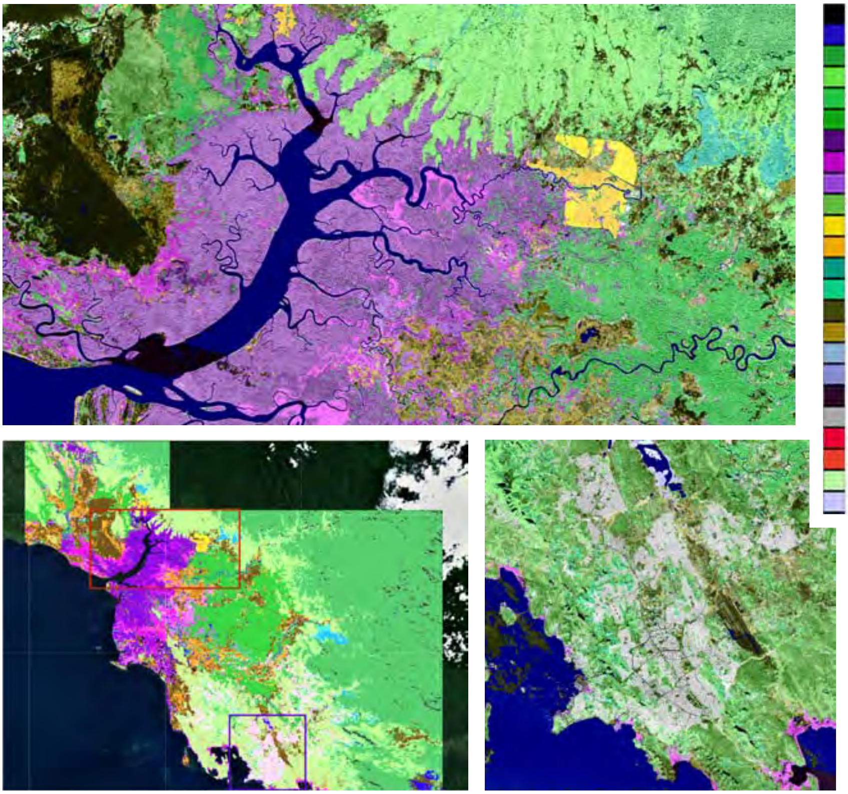



**Figure 9.** Land-cover classification of Papua New Guinea based on synthetic aperture radar. Bottom left: the total area covered, ~5,000 km$^2$, with inset boxes indicating the location of detailed images, top and bottom right. In the detailed imagery the classification has been overlaid onto multi-looked X-band imagery to aid interpretation.

| | short mangrove | water | tall mangrove | grass-baresoil | other mangrove | short vegetation-scrub | other plantation | shadow | other forest | secondary forest | savannah | mature rubber plantation | mature teak | logged teak | urban | swamp - weed thick | swamp - weed thin | young rubber plantation | primary forest |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| short mangrove | **162** | 0 | 27 | 0 | 4 | 7 | 1 | 0 | 11 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| water | 0 | **1831** | 1 | 12 | 0 | 1 | 0 | 0 | 1 | 0 | 2 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| tall mangrove | 23 | 3 | **2507** | 2 | 14 | 4 | 0 | 0 | 59 | 9 | 4 | 4 | 0 | 3 | 0 | 0 | 0 | 0 | 1 |
| grass-baresoil | 0 | 17 | 3 | **421** | 0 | 66 | 0 | 0 | 0 | 7 | 30 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 1 |
| other mangrove | 1 | 0 | 15 | 0 | **44** | 3 | 1 | 0 | 3 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| short vegetation-scrub | 3 | 0 | 3 | 50 | 2 | **128** | 0 | 0 | 2 | 5 | 14 | 0 | 0 | 4 | 0 | 1 | 0 | 1 | 0 |
| other plantation | 0 | 0 | 0 | 0 | 1 | 0 | **3** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| shadow | 0 | 3 | 0 | 0 | 0 | 0 | 0 | **478** | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 |
| other forest | 11 | 0 | 58 | 0 | 5 | 2 | 0 | 0 | **882** | 35 | 6 | 14 | 5 | 2 | 20 | 1 | 0 | 3 | 2 |
| secondary forest | 1 | 1 | 4 | 5 | 0 | 4 | 0 | 0 | 12 | **1890** | 31 | 1 | 30 | 8 | 17 | 0 | 0 | 2 | 239 |
| savannah | 1 | 1 | 2 | 30 | 0 | 17 | 0 | 0 | 12 | 19 | **1356** | 0 | 1 | 13 | 15 | 1 | 0 | 0 | 4 |
| mature rubber plantation | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 4 | 3 | 0 | **101** | 2 | 0 | 1 | 0 | 0 | 5 | 0 |
| mature teak | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 12 | 1 | 0 | **300** | 2 | 2 | 0 | 0 | 0 | 10 |
| logged teak | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 11 | 5 | 0 | 3 | **43** | 3 | 0 | 0 | 1 | 3 |
| urban | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 24 | 15 | 17 | 0 | 1 | 1 | **932** | 0 | 0 | 0 | 4 |
| swamp - weed thick | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | **25** | 2 | 0 | 0 |
| swamp - weed thin | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | **13** | 0 | 1 |
| young rubber plantation | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4 | 0 | 0 | 0 | 0 | 0 | **80** | 0 |
| primary forest | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 1 | 133 | 6 | 0 | 10 | 3 | 3 | 0 | 0 | 0 | **7898** |

| Class | % |
|---|---|
| short mangrove | 75 |
| water | 99 |
| tall mangrove | 95 |
| grass-baresoil | 77 |
| other mangrove | 64 |
| short vegetation-scrub | 60 |
| other plantation | 75 |
| shadow | 99 |
| other forest | 84 |
| secondary forest | 84 |
| savannah | 92 |
| mature rubber plantation | 86 |
| mature teak | 91 |
| logged teak | 62 |
| urban | 94 |
| swamp - weed thick | 93 |
| swamp - weed thin | 93 |
| young rubber plantation | 94 |
| primary forest | 98 |
| Overall | 93 |

**Figure 10.** Confusion matrix for the classification of Figure 9, and class classification accuracies (right)

At the simplest level, the SAR data available to PNG may be used to recover estimates of forest cover. This is possible using the GeoSAR data collected in 2006, as well as the PALSAR data available at later dates. To illustrate the point, Figure 11 shows a tile of 2006 GeoSAR data overlaid onto the false colour composite 2007 PALSAR data of Figure 6. The cleared forest areas to the north of the lake are visible in both datasets.

With regard to temporal variation, since high-resolution, wide-area SAR observations are available at regular intervals, and it is possible to use them to distinguish forested from non-forested areas, SAR permits a route to satisfying the United Nations REDD+ requirements for measurement, reporting and verification activity. The sophisticated techniques required to interpret and extract information from SAR imagery are available, and their combination with the unique SAR data library available to PNG could, with the right will, place the country at the global forefront of forest reporting.

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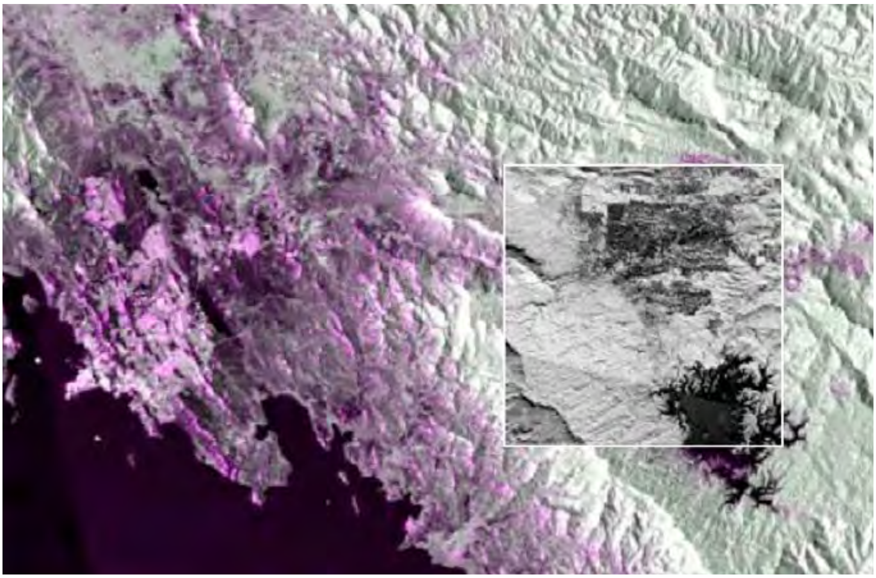

**Figure 11.** PALSAR L-band data from 2007 with (inset) a single tile of multi-looked GeoSAR P-band HH data from 2006

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# Impact of selective harvesting on litter-fall carbon stock in the lowland rainforests of Mongi-Busiga, Papua New Guinea

**Patrick L. Nimiago[1*], Nalish Sam[1] and Mathias Niangu[1]**

*Abstract*

Litter fall is an important pathway for the cycling of organic matter and chemical nutrients in forest ecosystems. This paper examines litter-fall production in harvested and primary forest of Mongi-Busiga, Finschhafen, Morobe province, to determine changes due to the effects of harvesting since 1999. Monthly litter fall was collected using litter traps established in 25 quadrates of each of two 1-hectare plots. From 1999 until 2008 dried litter was separated and weighed, and mean litter production was estimated to be 8.54 (t/ha/year) and 9.45 (t/ha/year) for the harvested and primary forest respectively. Litter biomass was converted to carbon (C), with estimated values ranging from 2.6 to 5.4 t C/ha/year in harvested forest and 3.8 to 5.5 t C/ha/year in primary forest. The highest litter fall occurred during drier months. The influence of selective harvesting on litter production was minimal, as the harvested forest had litter input from early successional species within the first year. Litter production from the primary forest plots showed a production pattern indicative of mature evergreen wet rainforest. The study supports the development of methodologies for the measurement of C stock from all pools in the natural forests of Papua New Guinea.

## Introduction

The Papua New Guinea Forest Authority (PNGFA) is legally mandated to manage the forest resources of Papua New Guinea (PNG), and is aware of the impact of forestry on global climate change and the vital role of forests in the national government's development strategies. PNG is recognised as a nation rich in tropical forest with the potential to contribute to global climate change mitigation programs. PNGFA is committed to reducing emissions from deforestation and forest degradation (REDD), and the enhancement of forest carbon (C) stocks and sustainable forest management (REDD+).

Forest assessment efforts in PNG need to be intensified to provide much-needed data on forest C, in particular pools other than live trees. Studies need to cover different forest types, geographical regions, land-use or management types (such as harvested forests), and plantations and agricultural lands to capture variability in these different systems. There are very few detailed scientific studies of C pools for PNG. However, there are some assessments of C stocks focusing on estimation of biomass and C from above-ground pools using data from permanent sampling plots (PSP) (Fox et al. 2010).

Litter fall is an important pathway for the cycling of organic matter and chemical nutrients in forest ecosystems. Litter-fall measurements are usually instituted to determine the mass of litter for assessment of forest ecosystem nutrient status. Studies on nutrient cycling and litter production have been undertaken in many different tropical forests around the world (Sundarapandian and Swamy 1999). In PNG such studies were undertaken by Edwards (1977), Edwards and Grubb (1977) and Grubb and Edwards (1982) in the high-altitude forest of New Guinea. The study detailed in this paper analyses

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litter production from a low-altitude evergreen wet tropical forest, and attempts to relate changes in the forest to the effects of harvesting on the forest ecosystem. Initial establishment reports of this study were done by Abe et al. (2000). Specific aims of this study were to:

1. determine litter production of lowland mixed-species rainforest
2. investigate impacts of harvesting on litter production pathways for nutrient cycling
3. assess what damage to the ecosystem is attributable to harvesting.

Furthermore, estimation of litter biomass from litter traps provides an opportunity to estimate C stock from fine litter, utilising 9 years of measurement data. Hence, this report also includes C stocks estimated from litter biomass, providing insight into the previously undescribed lowland rainforest fine-litter C pool.

# Methodology

## Research site

The study site is near Busiga village about 15 km south-west of Gagidu, the headquarters of Finschhafen district in Morobe province. The plots are at 6°40'57"S and 147°45'45"E, at altitude ranging from 111 to 146 m above sea level and within the Mongi-Busiga Forest Management Agreement area. Average annual precipitation in Finschhafen is 4,417 mm and the average mean temperature is 26.3 °C (McAlpine et al. 1975, cited by Abe et al. 2000). The average lowest monthly precipitation is 95 mm, although there is no distinct dry season reported. The average monthly rainfall, recorded in the field from 2003 to 2009, ranged from 181 mm for December to 1,178 mm in July (Figure 1). The difference between the hottest and coolest monthly mean temperature is about 2.1 °C.

The study area consists of 2 hectares (ha) of forest surrounded by new and old abandoned garden sites on low hills. The research site is owned by a clan from Busiga village and is on a lease arrangement.

## Forest structure and species composition

Two 1-ha permanent plots (100 × 100 m) were established in 1998. One plot was selectively harvested in 1998, while the other was left undisturbed for the purpose of this experiment. The plots are hereafter referred to as harvested forest (P1) and primary forest (P2; also referred to as undisturbed forest). Each plot was divided into subplots—20 × 20 m for trees (> 5 cm diameter at breast height (dbh)), 5 × 5 m for saplings (< 5 cm dbh) and 1 × 1 m for seedlings up to 2 m height. All trees and palms greater than 5 cm diameter were identified and their diameter recorded annually.

The original species composition was similar in both the harvested forest and primary forest. The upper canopy layer is dominated by *Pometia pinnata*, *Madhuca leucodermis*, *Palaquium amboinense*, *Syzygium gonatanthum*, while the canopy layer is occupied by *Canarium* spp., *Dysoxylum* spp.,

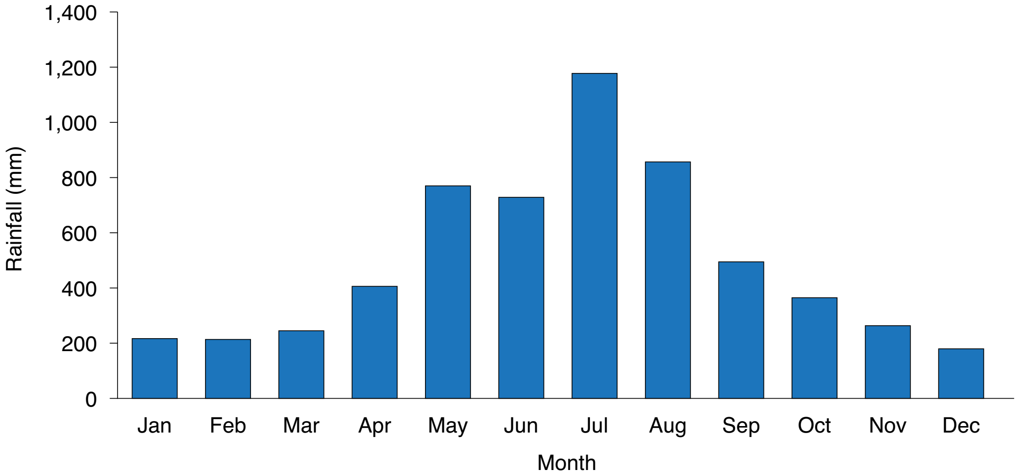


**Figure 1.** Average monthly rainfall at Finschhafen, 2003–09

*Elaeocarpus* spp. and *Terminalia* spp. Below the canopy is dominated by *Gymnacranthera paniculata*, *Haplolobus floribundus*, *Pimelodendron amboinicum* and *Myristica* spp. Palm species such as *Hydriastele microspadix*, *Pandanus* spp. and *Schefflera stahliana* are predominant in the lower tree layer.

The basal area of the harvested forest was 32.7 $m^2$/ha prior to harvesting (Abe et al. 2000), and was reduced during selective harvesting to 28.9 $m^2$/ha in 2005 (Table 1). After harvesting, secondary species and genera such as *Musa* spp., *Carica papaya, Pipturus, Paraserianthes falcataria*, *Piper, Homalanthus, Trema, Trichospermum* and *Abroma* regenerated rapidly, filling the gaps in P1. By 2009 almost 90% of these species disappeared due to the closing of the forest canopy. Unlike P1, the species composition of P2 (primary forest) remained relatively unchanged. The undisturbed forest plot represents a mature forest with an initial basal area of 45.7 $m^2$/ha in 1998 (Abe et al. 2000), which decreased to 43.3 $m^2$/ha in 2005 (Table 1) because of disturbance created when a large tree fell down in 2004.

## Litter-fall sampling

The sampling technique employed here varies slightly from the methods previously described for measurement of dead organic matter (Pearson et al. 2007; BioCarbon Fund 2008). The main difference is that litter-fall sampling in this study was primarily based on fine litter from traps that exclude coarse litter (branches >1 cm diameter) and ground fine litter, which is typically almost decomposed. Our method is very similar to methods designed for estimating primary production of forests by the International Biological Programme (Newbould 1967), and in the RAINFOR Field Manual, for measuring tropical forest C allocation and cycling (Metcalfe et al. 2009).

Litter traps were erected in both P1 and P2 in March 1999. One litter trap was set up in each of the 25 quadrates in each plot. The litter trap consisted of nylon mesh tied to three bent polyurethane poles 110 cm high. The collecting circular area was 0.5 $m^2$ (Figure 2). Every month, 25 samples of litter were collected from each of the two plots. Where traps were missing or damaged, it was assumed that no litter fall was recorded during the month of collection

Fine litter fall was collected in a plastic bag separately for each quadrat, and air dried initially then oven dried at 60 °C to constant weight. Each sample was separated into components and weighed as:

- leaf
- flowers, fruits, seeds
- bark, branches
- faunal litter
- trash material.

**Table 1.** Status of the harvested and primary forests of Busiga in 2005

| Species | Harvested forest (P1) | | Primary forest (P2) | |
|---|---|---|---|---|
| | N (N/ha) | BA ($m^2$/ha)[a] | N (N/ha) | BA ($m^2$/ha)[a] |
| *Dysoxylum pettigrewianum* | 30 | 0.33 | 24 | 0.09 |
| *Elaeocarpus meigei* | | | 3 | 0.22 |
| *Gymnacranthera paniculata* | 59 | 1.56 | 122 | 3.13 |
| *Haplolobus floribundus* | | | 113 | 1.34 |
| *Intsia bijuga* | 16 | 0.64 | 4 | 0.49 |
| *Madhuca leucodermis* | 31 | 6.30 | 73 | 15.15 |
| *Myristica aff. cucullata* | 50 | 0.69 | | |
| *Myristica globosa* | 45 | 0.75 | 23 | 0.14 |
| *Myristica subalulata* | 48 | 0.69 | 67 | 0.69 |
| *Palaquium amboinense* | 35 | 0.97 | 20 | 1.90 |
| *Pimelodendron amboinicum* | 20 | 0.59 | 31 | 1.00 |
| *Pometia pinnata* | 52 | 7.32 | 33 | 10.90 |
| *Schefflera stahliana* | 28 | 0.21 | 35 | 0.25 |
| *Macaranga aleuritoides* | 29 | 0.33 | | |
| *Syzygium gonatanthum* | 50 | 0.46 | 50 | 0.83 |
| Others (Pl 92 spp. P2 88 spp.) | 581 | 8.06 | 402 | 7.17 |
| Total | 1,074 | 28.90 | 1,000 | 43.30 |

[a] BA = basal area

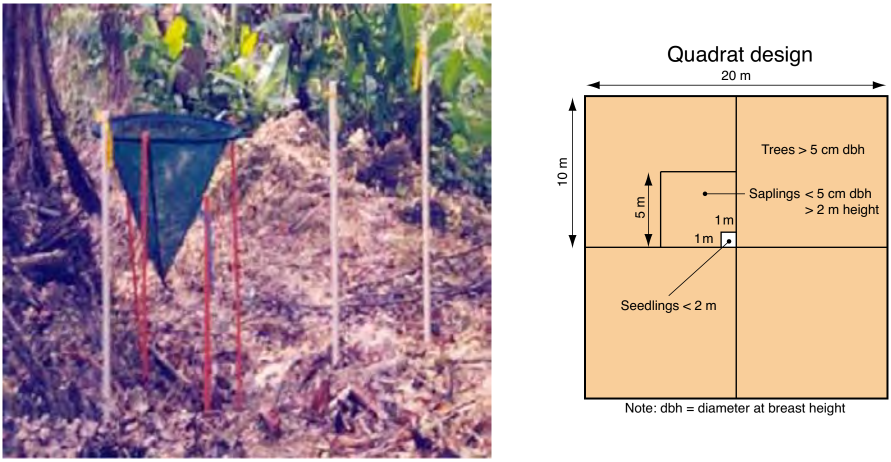


**Figure 2.** Litter trap design (Photo: Hitofumi Abe)

Trash material consists mainly of unidentified mixed material that was decomposed and inseparable. Monthly data during 2000–09 were stored on a spreadsheet and subsequently analysed. All litter was measured in grams; and dry weights were converted to t/ha for each month and t/ha/year for annual production.

Carbon is estimated to be half the biomass (Pearson et al. 2005).

## Results

Average monthly production of litter in the P1 and P2 forests exhibited similar patterns. A high monthly litter production of over 0.8 t/ha was registered for November, December, January and February, while in the other months litter production was between 0.5 and 0.8 t/ha. There was no distinct pattern of production, except that heavy litter fall tended to occur in dry months and lighter litter fall over wet months. The average monthly rainfall for the site is very high and can exceed 800 mm (Figure 1). However, most rainfall occurs from May to September, while the drier months are from October to April.

Monthly production in P2 was higher than in P1 in all months except June, July and December (Figure 3). In P1 the lowest was 0.52 t/ha in August and the highest 1.01 t/ha in December. In P2 the lowest was 0.55 t/ha in June and the highest 1.00 t/ha in December.

Average annual litter (biomass) production for P1 and P2 forests was 8.54 t/ha/year and 9.43 t/ha/year respectively. Annual production in P1 was lower than P2 for all years except 2002, 2004 and 2005, when it was slightly higher than P2 (Figure 4). The leaf-litter production amounted to 6.9 t/ha/year in P1 and 7.5 t/ha/year in P2. In both forest types leaves accounted for 80% of all litter components (Table 2).

Although P1 was harvested in 1998, the forest opening closed very rapidly through growth of secondary species. In 2005 P1 had more trees—1,074 stems/ha—compared with P2 at 1,000 stems/ha (Table 1). This is attributed to incursion by early pioneer species, which included several *Macaranga* spp., *Musa* spp., *Ficus* spp. and *Piper adicum*, which were absent in P2.

Carbon from litter follows the same patterns as for the biomass of litter produced within the forests (Table 3). The leaf component of the litter accounted for the most C, followed by branches and bark, while flowers, seeds and trash material contributed a very small amount (Table 2). The annual average C production was 4.2 t/ha/year for P1 and 4.6 t/ha/year for P2.

## Discussion

Ten years of data collection indicated that, after harvesting, average litter production at Busiga forest was able to recover to pre-disturbance levels within less than 3 years. The difference attributable to inter-site variation was thought to be small, as the plots are in the same forest and only a small distance apart. However, litter-fall production may be disrupted by harvesting, as indicated by the increase from 5.3 t/ha/year in 1999 during harvesting to 9.4 t/ha/year in 2000 after harvesting (Table 3). We observed that both monthly and annual litter production were not particularly affected by the removal of large trees. Litter traps were far below the canopy; therefore, litter inputs arose from the surrounding vegetation rather than a single tree.

Differences in litter fall between the two sites may be attributable to changes in species composition. The greatest changes occurred in P1, where early successional species emerged rapidly within 1–2 years following the opening up of the forest. In terms of species, the main differences between the plots were that P1 had the additional species, *Macaranga tanarius, Macaranga aleuritoides, Trichospermum*

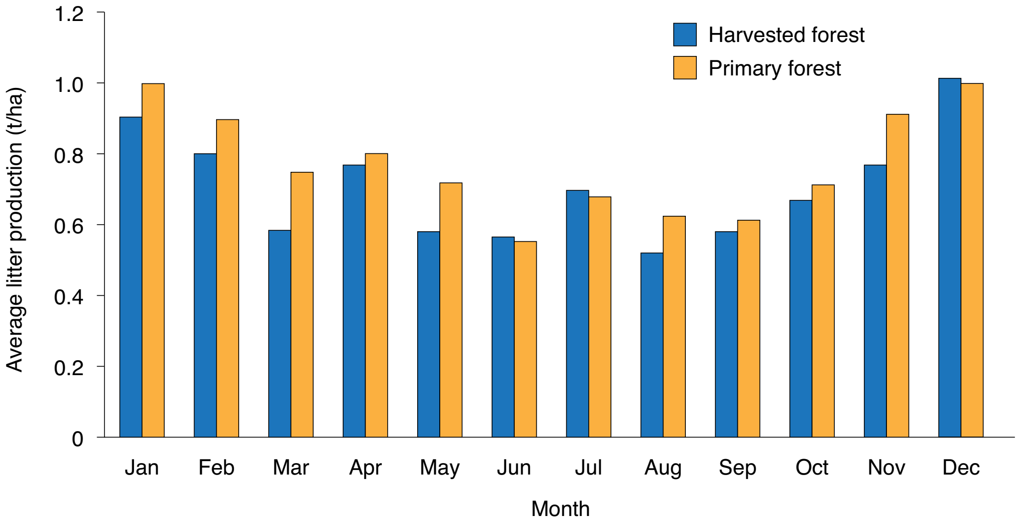


**Figure 3.** Average monthly litter production for 1999 to 2008 in the harvested and primary forests

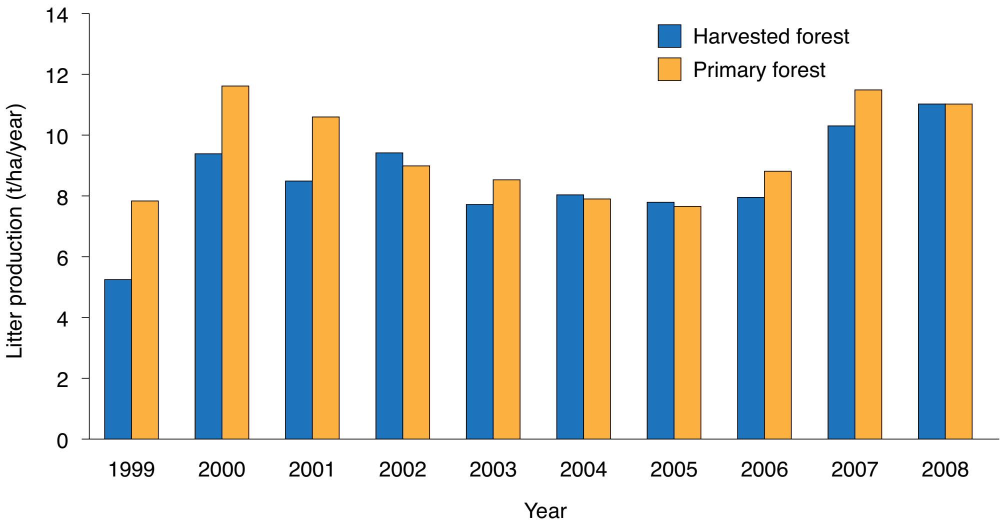


**Figure 4.** Annual litter production in the harvested and primary forest

**Table 2.** Mean annual litter production (t/ha/year) and carbon stock (t C/ha/year) by litter components in harvested and primary forests

| Litter components | Harvested forest | | Primary forest | |
|---|---|---|---|---|
| | Litter biomass | Carbon | Litter biomass | Carbon |
| Leaf | 6.9 | 3.4 | 7.5 | 3.7 |
| Flower and seed | 0.5 | 0.3 | 0.4 | 0.2 |
| Bark and branch | 0.8 | 0.4 | 1.2 | 0.6 |
| Faunal litter | 0.2 | Not applicable | 0.2 | Not applicable |
| Trash material | 0.1 | 0.05 | 0.2 | 0.1 |

**Table 3.** Total annual litter production (t/ha/year) and carbon stock (t C/ha/year) from 1999 to 2008 in harvested and primary forests

| Year | N* | Harvested forest | | Primary forest | |
|---|---|---|---|---|---|
| | | Litter biomass | C | Litter biomass | C |
| 1999 | 7 | 5.3 | 2.6 | 7.8 | 3.9 |
| 2000 | 12 | 9.4 | 4.5 | 11.6 | 5.6 |
| 2001 | 9 | 8.5 | 4.1 | 10.6 | 5.1 |
| 2002 | 10 | 9.4 | 4.6 | 9.0 | 4.4 |
| 2003 | 12 | 7.7 | 3.8 | 8.5 | 4.2 |
| 2004 | 12 | 8.1 | 4.0 | 7.9 | 3.9 |
| 2005 | 12 | 7.8 | 3.8 | 7.7 | 3.8 |
| 2006 | 10 | 7.9 | 3.9 | 8.8 | 4.3 |
| 2007 | 7 | 10.3 | 5.0 | 11.4 | 5.5 |
| 2008 | 6 | 11.0 | 5.4 | 11.0 | 5.4 |

N* = number of monthly litter collections

*pleiostigma, Trema orientalis, Pipturus argenteus, Piper aducum, Octomeles sumatrana, Ficus nodosa, Ficus variegata, Clerodendron tracyanum, Commersonia bartramia, Endospermum medullosum, Carica papaya, Anthocephalus chinensis* and *Paraserianthes falcataria.* The regeneration behaviour observed in P1 suggested that species occurred depending on the presence of seeds and the ability to compete for light, nutrients and space.

Litter production in forests is defined by forest type and influenced by seasonal and climatic fluctuations. Our litter-fall estimates (Table 4) are slightly higher than figures from Penang and Sarawak, and slightly lower than Pasoh, Malaysia; Manaus, Brazil (Smith et al. 1998; Whitmore 1998); and North Queensland, Australia (Stocker et al. 1995; Whitmore 1998). Our results are very different to those from Indian forests, where litter fall was about 50% higher in humid rainforests and about 20–80% lower in deciduous forests (Sundarapandian and Swamy 1999). The results from Busiga reported in this study are slightly higher than those reported for the PNG highlands (Edwards 1977).

Production of C was directly related to litter production in the two plots (Table 3), with P2 typically having slightly higher average monthly and yearly litter fall compared with P1.

Brown (1997) reported that the biomass density of fine litter of tropical forests from various countries constituted approximately 5% of above-ground biomass. Litter comprised 2% of C stock out of a total of 202 tC/ha for tropical forest in Bolivia (Noel Kempff Climate Action project; GOFC-GOLD 2008). Pearson et al. (2005) reported litter to be 2.8 tC/ha compared with live above-ground trees (123.3 tC/ha) from 111 plots in Belize (i.e. 2%). In this study C stock from litter ranges from 2.6 to 5.4 t/ha/year in P1 and 3.8 to 5.5 t/ha/year in P2. Although litter does not constitute a large C pool, compared with other above-ground pools, below-ground biomass and dead wood, it is important as a transient pool of C that is eventually transferred to a permanent pool in organic

**Table 4.** Total litter fall from this study and some other forest types

| Forest type | Location | Litter production (t/ha/year) | Source |
|---|---|---|---|
| Tropical lowland rainforest—harvested | Busiga, PNG | 8.5 (5.3–11.0)* | This study |
| Tropical lowland rainforest— mature intact | Busiga, PNG | 9.4 (7.7-11.4)* | This study |
| Lowland evergreen rainforest | Penang, Malaya | 7.5 | Whitmore (1998) |
| Lowland evergreen rainforest | Sarawak, Kalimantan | 7.7 | Whitmore (1998) |
| Lowland evergreen rainforest | Pasoh, Malaya | 10.6 | Whitmore (1998) |
| Lowland evergreen rainforest | Manaus, Brazil | 7.4–8.2 | Smith et al. (1998) |
| Tropical rainforest | North Queensland, Australia | 7.04–13.64 | Stocker et al. (1995) |
| Humid rainforest | Nelliampathy Kerala, India | 17.5 | Sundarapandian (1999) |
| Deciduous | Varanasi, India | 1.0–6.2 | Sundarapandian (1999 |
| Montane rainforest | Highlands, PNG | 6.8–7.7 | Edwards (1977) |

* Denotes range

and mineralised soil C, if not lost in forest fires. This study suggests that litter production after disturbance may be faster to recover compared with other C pools. For a disturbed tropical forest, recovery of the above-ground biomass is slow, as observed for forest fallows in Sarawak, Malaysia, at 12.7 tC/ha (Jepsen 2006).

In this study selective harvesting appeared to have only a small effect on litter production. Litter recovered quickly due to input from early successional species that regenerated in the openings. Tree species in Busiga forest are mainly evergreen and tended to shed leaves through senescence processes, as observed from individual species phenology. As leaf litter made up the bulk of litter biomass and C, and leaf-litter fall under normal forest conditions is influenced by both wet and dry periods, we postulate that local climate was a major influence on litter fall in P1.

Estimates of C stock from litter, as a component of the dynamic forest C pool, are valuable as they are indicative of C temporarily held in the fine litter component of dead organic matter. The forests of PNG are typically heterogonous in species composition, climate, elevation, land use and disturbance history. This study provides input for decision-making on which land areas to sample, and which C pools to evaluate, considering the availability of time and money and appropriate methodology.

## Acknowledgments

The litter studies in Busiga were initiated under funding from Japan International Cooperation Agency (JICA) in the second phase of project assistance to PNGFRI. Several people then attached to the PNGFRI JICA project under the ecosystem management section—Pelis Vatnabar, Nalish Sam, Mathias Niangu and Hitofumi Abe—were involved in establishing the permanent sampling plots and litter traps. Monthly litter and daily rainfall data were collected and recorded by Kitu Naeman and family of Busiga village. Drying and weighing in the laboratory was undertaken by Kepas Davis, Brian Samba and Schola Yopiyopi.

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# Assessment of forest soil carbon stock in Papua New Guinea

**Patrick L. Nimiago[1*]**

*Abstract*

This paper presents indicative forest soil carbon stock measurements derived from assessment of permanent sampling plots established by the Papua New Guinea Forest Research Institute. Two soil-sampling designs were used on selected sites representing harvested and primary forests, and different altitudes, land uses and management types. Twelve subplots were systematically sampled within each permanent sampling plot; extracted soil samples from 30 cm depth were subdivided, oven dried at 40 °C and weighed; bulk density was determined on dry weight at 105 °C; and organic carbon was measured on the CN analyser, vario MAX. Results indicated high variability in forest soil carbon content; the lowest was 31.27 t/ha in Danar in a lowland and highly disturbed site, while the highest was 112.95 t/ha in undisturbed Watut high-altitude cool moist forest. This initial work in carbon stock assessment of forest soils is useful in relation to the 2006 Intergovernmental Panel on Climate Change guidelines, while country-specific values can assist Papua New Guinea move away from Tier 1 reporting and has also set the foundation for further soil carbon assessment work as proposed in the national inventory of forest carbon pools.

## Introduction

The changing global climate has been attributed to increasing greenhouse gases, and deforestation and degradation of tropical forests has been estimated to be responsible for approximately 20% of global anthropogenic emissions of carbon dioxide ($CO_2$). Former Prime Minister Sir Michael Somare has strongly endorsed Papua New Guinea's (PNG's) participation in the international climate change mitigation initiative REDD+ (reducing emissions from deforestation and forest degradation and enhancement of forest carbon (C) stocks). Internationally, PNG has been at the forefront of negotiations on REDD+, and it is important that PNG forest scientists collate available information on forest C stocks and collect new data. There has been some work on estimating C stock in above-ground live biomass (Fox et al. 2010) but little work on other forest C pools. This paper will describe a preliminary assessment of soil C stock of forests in PNG.

Forest soils are a reservoir for plant nutrients, containing a significant proportion of C in comparison with other elements. The amount of C in forest soils reflects C that originated from mineralised organic matter (organic C) as well as inorganic C from original parent material. Carbon storage in soils is dynamic and is influenced by soil types and land uses, which could change a forest area from being a sink to a source for $CO_2$ if land use changes. This paper outlines methodology for the sampling of soil organic carbon (SOC), inclusive of a plot design conforming to the general methodology from the Intergovernmental Panel on Climate Change (IPCC 2006). Preliminary results are also presented. This work on soil C quantification for PNG is a component of a larger body of work, estimating the entire forest C stock, undertaken in joint collaboration with the Max Plank Institute of Biogeochemistry (MPI BC) of Germany during 2007. The main objectives of the work were to generate initial data on PNG forest C stocks to support the REDD agenda at the Bali Conference of Parties, and to provide capacity building of national scientists to enable them to undertake high-quality work.

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# Methods

Soil sampling covered four permanent sampling plots (PSP) and one temporary plot (Table 1) due to time and financial constraints. The general procedures for site selection, sampling design, equipment used, and calculations and estimation of C in soils are as prescribed by the 2006 IPCC guidelines. The field sampling and laboratory procedures are similar to accepted standard procedures by Pearson et al. (2007) and the BioCarbon Fund (2008).

## Site selection

Soils vary from place to place and change gradually over time. Different climatic conditions and land uses influence the distribution of soil C; therefore, selection of sites in this preliminary investigation targeted different altitudes, climates, vegetation and forest management types. Sampled sites in the feasibility study had GPS locations recorded for possible geographic information systems analysis and mapping in future (Table 1).

## Plot design and field sampling

There are many sampling methods that can be used to give precise and accurate results for soil C assessment. Systematic or random sampling designs within the selected sampling area can be used, depending on the purpose and scope of the survey. Usually, the sampling method is designed to cover the area, capturing the natural variability and land-use categories and changes over time. In this study, undertaken by PNG Forest Research Institute (PNGFRI) and the MPI BC team, the focus was on sampling within PSPs, as it is more relevant and realistic to measure all preferred C pools in the fixed research plots that have been specifically established to monitor forest dynamics in the cutover and intact forests.

Sampling within the PSPs was concentrated in the 20 × 20 m quadrats laid out systematically, with soil sampling done in the shaded quadrats in Figure 1. In all, 12 quadrats were sampled from a total of 25 quadrats within each PSP. For an area in Watut 7, a temporary plot was established (Figure 2). A reference point was established that will be recognisable in future. From the starting point, four transects were measured, with the two base lines perpendicular and two interior lines at 30 degrees apart. Nine sample points were set up on this site. This sampling design, which was trialled for the first time in this study, is recommended for rapid forest soil surveys covering large areas.

Soil sampling was located in the centre of the PSP or the transect line in temporary plots. A temporary area of 30 × 30 cm was set up, then litter was collected and soil samples were extracted using a soil corer driven into the soil manually (Figure 3). The bulk of SOC is generally concentrated in the 0–15cm soil layer, although this may vary in forest soils (Lal 2005). It is generally assumed that over 50% of C in soil is usually within the first 30 cm for undisturbed sites. Literature on SOC reviewed by the IPCC (2006) supports this assumption. In the soil's upper zone the C input is mainly from decayed organic material. This is also regarded as the top soil layer, where C content is vulnerable to changes by natural agents or human activities. Due to practicality of sampling and the associated costs involved, sampling of soils in the PSPs was concentrated only to 30 cm depth.

Soils samples were extracted using the soil core (split-tube sampler; Figure 3). Soil samples were subdivided into depth increments—0–5, 5–10. 10–20, 20–30 cm. A representative sample of 100 $cm^3$ was obtained for bulk density measurements, which are required prior to chemical analysis. Samples were collected from the bottom up. They were placed in sealed bags that were clearly labelled and transferred back to the laboratory.

## Soil treatment

All mineral and organic material was oven dried at 40 °C. Samples for bulk-density determination were weighed and sieved to isolate the fine earth

**Table 1.** Sampling site characteristics

| Plot and location | Altitude (m) above sea level | Forest type | Management |
|---|---|---|---|
| Kui, Morobe province | 2–20 | Coastal lowland | Harvested before 1990 |
| Watut 3, Morobe province | 2,170 | Montane | Harvested in 1995 |
| Watut 7, Morobe province | 2,190 | Montane closed | Intact primary |
| Danar 1, Madang province | 140 | Lowland secondary | Shifting cultivation |
| Danar 3, Madang province | 152 | Lowland | Harvested in 2006 |

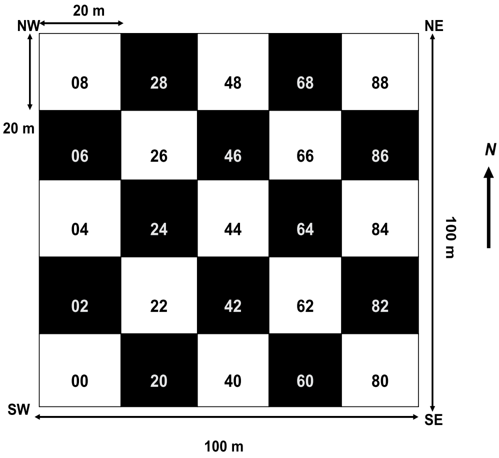


**Figure 1.** PSP plot design and location of soil sampling in shaded quadrats

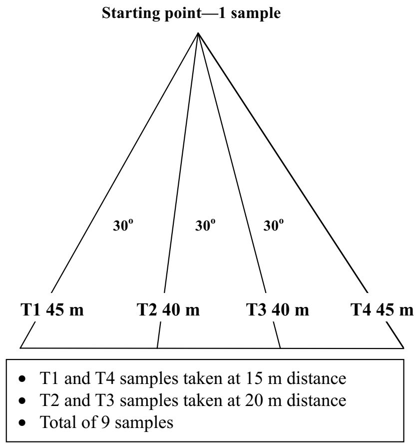


**Figure 2.** Sampling design for transects in temporary plot

**Figure 3.** Soil coring using split-tube sampler

fraction (< 2 mm), and then dry mineral fine earth was weighed and stored in airtight sealed bags. Dried litter material was also weighed, and then ground and reweighed. All samples were packed and taken to Germany, where chemical analyses were undertaken in the MPI BC laboratory.

## Carbon measurement using CN analyser

The procedures outlined below are based on work undertaken to determine SOC using the dry combustion CN (carbon and nitrogen) analyser, vario MAX. The soil and organic material were further ground to very fine material using a mechanical grinder. All weight measurements were done on scales attached to the computer that maintained checks for accuracy of measurements and for rapid transfer of data to computers attached to CN analysers.

Subsamples from each sample were weighed and then oven dried at 105 °C for 48 hours for determination of moisture content. Samples of 240–280 mg were weighed onto ceramic cups, followed by addition of 0.40–0.45 g of tungsten oxide. Every fifth sample in sequence was replicated twice for quality checking. Standards for measurements were prepared—the first two in the range 24.00–25.99 mg, and the next two containing 5.00–6.00 mg with

400–500 mg of tungsten added. Prepared samples including standards and blanks were placed on the autosampler sequence of the CN analyser and automatically taken in for combustion. The measurements were recorded on a computer under created files that were stored in a database.

### Calculation of carbon stocks

Moisture content was determined for the samples and then used in correcting the actual C content by dry weight. Soil sample density was determined from the dry weight and again corrected using subsample dry weight. The organic C data obtained from the CN analyser were converted to C (mg) on the basis of sample weight, and then converted to C content percentage (C%) based on the corrected dry weight of samples. Carbon % is then converted to C content (g/kg). Carbon stock (t/ha) was determined as C content (g/kg) multiplied by the corrected dry soil density (kg/m$^3$) by soil depth.

## Results

The preliminary soil sampling work in PNG comprised Kui on the coast near sea level, Danar in lowland forest and Watut in high-altitude mountain forest. Judging from the forest structure noted during the survey, Danar is located on an alluvial flood plain that is subjected to periodic floods and forest clearings. A systematic sample of 12 quadrats in each PSP was implemented, except in Kui where one quadrat was considered unsuitable because of a rocky outcrop. The summary of preliminary results from a total 224 samples from five sample sites is presented in Table 2.

Soil C varied greatly among the three areas. The high-altitude and cool cloudy Watut Mountains had twice the amount of C in soil compared with the lowland and coastal warm areas (Table 2). Very low soil C (31.27 t/ha) in Danar plot 3 reflects a high frequency of natural and human disturbances occurring in the area, including recent timber harvesting in 2006. Danar plot 1 is approximately 800 m away from Danar plot 3, and had slightly higher C because this area is less disturbed and the secondary forest is estimated to be recovering from shifting cultivation, which occurred 10–20 years ago. The amount of C in Kui soils (45.22 t/ha) is closer to Danar 1 (55.92 t/ha) and Danar 3 (31.27 t/ha). The Kui plot is laid on a slope that is about 50–100 m inclined away from the shoreline, while Danar is on flatter terrain. At both sites the soil structure is generally loose with sandy loam texture in the assessed zone. In contrast, the Watut soils are typically clay and retain moisture, including mineralised decomposed plant material that showed high C content. Watut 3 and Watut 7 had C stock of 112.95 t/ha and 102.78 t/ha respectively. Watut 3 had been harvested but there appeared to be less impact on the soil C stock or a remarkable build-up in a short time (11 years) after harvesting in 1995.

The Danar 3 plot had a high concentration of C in the first 5-cm layer and low amounts in the 10–30-cm zone. In Watut there appeared to be more C in soil deeper than the first 5 cm. From these results there may be more C in Watut soils beyond 30 cm depth, and further sampling is needed to determine the extent of this possibly significant C pool in similar high-altitude forest.

## Discussion

An inventory of SOC following IPCC guidelines is required to identify country-specific values, which can be used in preference to the very conservative default values, and can assist the PNG Government move beyond a Tier 1 compliant greenhouse gas inventory of forested land (IPCC 2006). The results from the initial sampling indicate that SOC varies considerably for different sites under different land uses and altitudes in PNG. For instance, the values for Danar and Kui in low-altitude forests were lower than for the high-altitude site, Watut (Table 2). The site at Danar is on a low alluvial plain that been subjected to shifting cultivation and other disturbances such as fire. Watut has experienced the least human activities, except that Watut 3 was harvested in 1995. The results for Watut 3 and Watut 7 suggest that C stock is still intact after harvesting. However, the impact of harvesting on C stock would have been better verified if the changes had been monitored before and after the harvesting event. High variations of natural conditions in tropical forest influence the soil properties, including C stock. The initial work described in this paper has set the foundation for further work within the country for a proposed national inventory of forest C pools. The sampling procedures have been standardised for consistency with IPCC guidelines. Qualified personal to undertake fieldwork are ready. Sampling schemes should be standardised nationwide to safeguard the consistency of results. A responsible and careful sampling with diligent pre-processing of the samples, as well as thorough documentation, will guarantee reliable results.

**Table 2.** Mean total soil carbon stock by site and soil depth (standard deviations in parentheses)

| Site | Sample no. | Carbon stock (t/ha) by soil depth | | | | |
|---|---|---|---|---|---|---|
| | | 5 cm | 10 cm | 20 cm | 30 cm | Total |
| Kui | 11 | 11.29 (5.60) | 8.70 (3.21) | 13.12 (3.50) | 12.12 (8.10) | 45.22 (11.28) |
| Danar 1 | 12 | 12.79 (2.85) | 10.02 (2.05) | 18.46 (4.56) | 14.65 (3.91) | 55.92 (5.56) |
| Danar 3 | 12 | 12.76 (3.77) | 7.19 (2.77) | 6.67 (3.69) | 4.65 (1.16) | 31.27 (8.55) |
| Watut 3 | 12 | 22.14 (4.17) | 19.13 (3.95) | 38.21 (11.20) | 33.46 (7.50) | 112.95 (21.38) |
| Watut 7 | 9 | 22.88 (6.12) | 20.44 (6.88) | 30.85 (7.82) | 28.60 (9.36) | 102.78 (22.78) |

In this feasibility study, five plots in two provinces were covered in 2007. Using Australian Centre for International Agricultural Research (ACIAR) funding from project FST/2004/061, further field surveys covering 14 PSPs were undertaken in five provinces during 2008 and 2009—four in Manus, two in West New Britain, two in Western province, four in Oro province and two in East New Britain. A total of 634 soil samples and 168 litter samples were collected from 144 quadrates; they were dried, weighed and homogenised, and currently await chemical analysis. The PNG FRI already has some equipment and the ability to undertake fieldwork correctly and consistency. It has some laboratory facilities, but it is unable to undertake laboratory CN tests at present due to little support for equipment or laboratory capacity building.

## Acknowledgments

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# Modelling

# Native forest individual-tree modelling in Papua New Guinea

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*Abstract*

Quantitative study of the permanent sample plot (PSP) database can provide insights into growth, mortality and recruitment processes driving forest dynamics. Modelling the dynamics of forest growth and yield provides opportunities for optimising silvicultural systems and generating accurate growth and yield estimates, which are fundamental to sustainable forest management. This paper will outline model development based on analysis of a large native forest permanent sample plot database in Papua New Guinea. We quantify the competitive influences affecting individual tree growth and mortality, and build predictive models for growth and mortality based on a hierarchical Bayesian modelling methodology. This method allows the parameterisation of a global model with species-specific parameters; therefore, species-level growth and mortality traits are preserved in model predictions, even for rare species. We examine a range of spatial and non-spatial competition indexes for the data, and conclude that a simple non-spatial competition index (basal area of competing trees within 20 metres of the subject) adequately characterises competitive influences on growth and mortality. In future work, species-specific model parameters can be used as the basis of a forest simulation system (see http://twoe.org for developments) to improve the design and intensity of selective-harvesting regimes at the community and the concession level.

## Introduction

Tropical forests cover 10% of global land area but remain a scientific frontier due to structural and biological complexity and high temporal variability associated with complex successional processes (Chambers et al. 2001). A constraint is the limited number of long-term studies quantifying tropical forest dynamics, and the impacts of anthropogenic and natural disturbances such as harvesting and fire (Clark et al. 2001; Lewis et al. 2009). Long-term studies, while difficult to maintain, especially in developing countries, are essential to the development and testing of hypotheses regarding processes and rates of ecological recovery following disturbance, both anthropogenic and natural (Taylor et al. 2008). The forests of Papua New Guinea (PNG) are structurally diverse and complex, and have rarely been studied. The comprehensive permanent sample plot (PSP) database provides an opportunity to ameliorate this. Quantitative study of the database can provide insights into growth, mortality and recruitment processes driving forest dynamics in PNG.

The development of growth and yield models for PNG's native forests has never been a priority for the PNG Forest Authority (PNGFA), and this limited development has hindered the effective management of native forest resources. The only exception to this is the work on growth and yield undertaken by Alder (1998), who developed a stand-level growth model

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called PINFORM based on the first remeasurement of a PSP dataset. Unfortunately, PINFORM has not been routinely applied by PNGFA for forest planning or sustainable yield purposes. However, growth and yield models can be used for optimising silvicultural systems and generating accurate growth and yield estimates, which are fundamental to sustainable forest management. As part of Australian Centre for International Agricultural Research (ACIAR) project FST/2004/061, the limited extent of growth and yield modelling in PNG has been advanced with the development of individual-tree models for competition, growth and mortality. In future work, models will be developed for recruitment, and will be integrated into a forest simulation tool. This tool, under development at <http://twoe.org>:

- manages and modifies PSP datasets for analysis of growth, mortality and recruitment
- estimates model parameters using hierarchical Bayesian modelling
- can be used to simulate forest dynamics.

The individual-tree growth modelling approach is sufficiently flexible to accommodate forests with virtually any species mixture or size structure. Individual-tree models are also age independent, making them applicable to uneven-aged stands, as are commonly encountered in tropical forests. Many alternative growth and yield modelling methodologies exist and have been reviewed elsewhere (e.g. Vanclay 1994). It is the flexibility of the individual-tree growth model that has led to its application to the native forest resource of PNG, as much of the resource exists in mixed-aged, mixed-species stands, often of indeterminate age.

Forest utilisation in PNG is increasingly occurring at the community level using small-scale sawmills to extract individual trees. This small-scale use is the basis of Forest Stewardship Council (FSC; an international body that outlines social, environmental and economic certification requirements) certification efforts that aim to empower landowners, improve livelihoods, preserve the natural environment, and facilitate sustainable development (Bun and Scheyvens 2007). To examine whether these operations are sustainable, growth models are required for predicting tree growth at the scale of the individual tree. They can then be used in community forestry to inform small-scale (individual-tree) scenario analysis, species-specific carbon sequestration, and the impact of small-scale utilisation on carbon stocks.

Individual-tree models characterise the competitive, growth, mortality and recruitment dynamics of individual trees—this is challenging in the complex and diverse tropical forests of PNG. This paper will outline model development based on analysis of the PSP network in PNG. We quantify the competitive influences affecting individual-tree growth, and build predictive models for growth and mortality based on a hierarchical Bayesian modelling (HBM) methodology (Fox et al. 2011a). One of the challenges with statistical analysis of PSP data is autocorrelation between measurements. Autocorrelation eventuates when spatial, temporal or hierarchical variation cannot be captured by deterministic model structures (such as a simple mean), reducing estimation efficiency and biasing hypothesis tests on estimated parameters (Fox et al. 2001). PSP data have implicit hierarchical structure—trees are nested within plots that are repeatedly measured through time and/or space. HBMs are applied here because they can facilitate the explicit modelling of autocorrelation (Clark 2005; Clark and Gelfand 2006; Cressie et al. 2009). The hierarchical Bayesian approach also quantifies the response of growth and mortality to competition and tree size across the entire tree community. Using HBMs with species random effects, the variability of the growth/mortality response between all species can be estimated, including rare species with few observations (Dietze et al. 2008).

Competition indexes have been the subject of much attention in the forestry literature. Distance-dependent indexes (DDIs) use the spatial positions of individual trees in their formulations whereas distance-independent indexes do not. Because DDIs incorporate the spatial pattern of competitors, it should follow that they provide an improved quantitative expression of competition. The various competition indexes can be organised into several groups. DDIs comprise distance-weighted size ratio indexes (e.g. Hegyi 1974), area overlap indexes (e.g. Bella 1971) and area potentially available indexes (e.g. Nance et al. 1987). They consist of functions of subject tree attributes compared with the attributes of other trees on the plot (e.g. Stage 1973), and stand-level indexes such as basal area per hectare (BA/ha) and stems/ha. The various competition indexes described above have been quantified for trees from the PSP database in PNG, and will be compared in terms of their ability to predict individual tree dynamics.

## Methods

### PSP data

Over the past 20 years the Papua New Guinea Forest Research Institute (PNGFRI) has established and remeasured over 125 PSPs across PNG covering all major forest types. Each plot is 1 ha in size and is divided into 25 subplots of 20 × 20 m. The spatial location, diameter, height and crown characteristics are recorded for all trees over 10 cm in diameter. The PSP database represents a strong basis for the development of individual-tree models. Because individual trees in PSPs are spatially mapped, the spatial competitive processes governing tree growth can be extricated. The PSP data are described in detail elsewhere (Fox et al. 2010). The PSP data are a compilation of plot remeasurements undertaken by PNGFRI since 1994. They have been affected by persistent errors that have hindered their usefulness for modelling. A considered error correction methodology was required to correct persistent errors affecting the PSPs as described in Fox et al. (2010). Following this, the PSP dataset was clean and ready for analysis. Figure 1 shows the PSP team for the Danaru PSPs remeasured in August 2008.

Initially, competition indexes are evaluated against individual tree growth for the PSP data. The outcomes of this evaluation then inform individual-tree model development for growth and mortality. Prior to evaluation of competition indexes, allometric modelling was required to determine species-specific relationships between diameter and crown diameter.

### Allometric modelling

Diameter – crown diameter (DCD) allometry is required to quantify individual-tree competitive dynamics. To achieve species-specific DCD models, several nonlinear models were fitted that were found to perform well for tropical forests in the study of Fang and Bailey (1998): the log-linear model (Alexandros and Burkhart 1992; equation (1)); the hyperbolic model (Huang and Titus 1992; equation (2)); and the exponential model (Fang and Bailey 1998; equation (3)):

$$H = a + bLogD \quad (1)$$

$$H = aD/(b + D) \quad (2)$$

$$H = a + b\left(1 - e^{-c(D - D_{\min})}\right) \quad (3)$$

where: $a$, $b$ and $c$ are parameters estimated for each of the tree species; $D_{\min}$ is the minimum observed diameter for the species.

**Figure 1.** Measurement team for Danaru permanent sample plots, August 2008 (Photo: Julian Fox).

Analysis revealed that the hyperbolic model (equation (4); see Table 2) had a consistently lower mean squared error across species represented on PSPs. It was thus selected for crown diameter prediction on PSPs. This is the same model that was used to describe diameter–height (DH) allometry in Fox et al. (2010). To predict individual-tree merchantable volume, the same model was fitted to diameter-merchantable height (DMH) allometry. Table 1 provides species-specific allometric parameters for DCD, DH, and DMH models for the 30 most numerous species on the PSPs.

Allometric parameters described in Table 1 are the basis of lookup tables in the forest assessment tool described in Fox et al. (2011b).

## Competition indexes

### *Distance weighted size ratio competition indexes*

The distance-weighted size ratio (DWSR) competition indexes include those that use the distance between trees weighted by their respective sizes in their formulations. Two of the most successful DWSR variants were quantified in this study: those of Hegyi (1974) and Newnham (1966). The Newnham index (equation (5)) quantifies local density as the sum of angles subtended from the subject to either side of the stems of competitors. The two DWSR indexes are described in Table 2.

The choice of which competitors to include when calculating DWSR indexes is an unresolved problem

**Table 1.** Individual-tree allometric parameters for the hyperbolic model fitted to diameter–height, diameter – merchantable height, and diameter – crown diameter models for the 16 most numerous species on PSPs

| Species | Sp. code | Character | **DH-*a*** | **DH-*b*** | **DMH-*a*** | **DMH-*b*** | **DCD-*a*** | **DCD-*b*** |
|---|---|---|---|---|---|---|---|---|
| *Calophyllum* sp. | CAL SP | climax | 66.1 | 43.7 | 30.5 | 32.7 | 49.6 | 217.9 |
| *Canarium* sp. | CAN SP | climax | 56.1 | 34.4 | 30.0 | 31.6 | 24.4 | 77.2 |
| *Celtis* sp. | CEL | climax | 71.5 | 49.0 | 31.7 | 38.9 | 22.3 | 65.9 |
| *Cryptocarya* sp. | CRY SP | climax | 50.2 | 30.3 | 24.6 | 25.4 | 18.2 | 54.0 |
| *Dysoxylum* sp. | DYS SP | climax | 55.1 | 38.8 | 24.2 | 29.3 | 19.3 | 54.2 |
| *Ficus* sp. | FIC SP | climax | 61.5 | 49.6 | 32.3 | 53.6 | 27.5 | 86.8 |
| *Garcinia* sp. | GAR SP | climax | 57.6 | 39.3 | 32.4 | 40.6 | 15.5 | 38.7 |
| *Horsfieldia* sp. | HOR SP | climax | 65.9 | 47.1 | 33.6 | 37.1 | 15.9 | 43.8 |
| *Litsea* sp. | LIT SP | climax | 55.7 | 36.4 | 28.5 | 32.4 | 16.5 | 47.6 |
| *Macaranga* sp. | MAC SP | pioneer | 52.7 | 36.5 | 28.6 | 40.7 | 10.9 | 21.8 |
| *Myristica* sp. | MYR SP | climax | 51.0 | 33.0 | 23.5 | 24.5 | 9.1 | 16.8 |
| *Pimeleodendron amboinicum* | PIM AMB | climax | 53.3 | 35.6 | 26.5 | 34.4 | 14.4 | 38.9 |
| *Planchonella* sp. | PLA SP | climax | 56.8 | 33.7 | 30.0 | 30.3 | 21.9 | 74.9 |
| *Pometia pinnata* | POM SP | climax | 53.1 | 32.4 | 25.5 | 30.5 | 21.0 | 58.7 |
| *Syzygium* sp. | SYZ SP | climax | 55.7 | 37.1 | 27.9 | 32.3 | 18.3 | 56.3 |
| *Terminalia* sp. | TER SP | climax | 62.4 | 41.1 | 38.9 | 48.0 | 20.6 | 56.9 |

**Table 2.** Distance-weighted size ratio competition indexes

| Index | Formulation | Author |
|---|---|---|
| *HEG* | $$HEG_i = \sum_{j=1}^{n_i}\left[\frac{D_j}{D_i} \times \frac{1}{Dis_{ij}}\right] \quad (4)$$ | Hegyi (1974) |
| *NEW* | $$NEW_i = \sum_{j=1}^{n_i} 2\left[\operatorname{atan}\frac{0.5D_j}{Dis_{ij}}\right] \quad (5)$$ | Newnham (1966) |

Note:
$n_i$ = total number of competitors for the subject *i*; $D_i$ = diameter at breast height for the subject tree *i*; *Dj* = diameter at breast height of the *j*th competitor; $Dis_{ij}$ = the distance in meters between the subject *i* and competitor *j*.

(Burton 1993). To reduce subjectivity in estimates of competitor search radius, a methodology was used whereby an optimal search radius (OSR) was identified mathematically for each species. This could also provide insight into the range of the competitive dynamic affecting particular rainforest species. By examining the relationship between index performance and competitor search radius, it was confirmed that index performance generally approached a maximum value asymptotically. The point at which performance first began to level off was then estimated mathematically using a segmented, nonlinear equation similar to the spherical semi-variogram employed in geostatistics (e.g. Journel and Huijbregts 1978). This segmented, nonlinear model was fitted to characterise the correlation of the index with growth and competitor search radius, and can be described in equation (6):

$$\begin{aligned} Corr_i &= \alpha\left[1.5(sr_i/\beta) - 0.5(sr_i^3/\beta^3)\right], \quad sr_i \le \beta \\ Corr_i &= \alpha, \quad sr_i > \beta \end{aligned} \tag{6}$$

where: $sr_i$ is the search radius ($i$ = 2–20 m at 2 m increments), $Corr_i$ is the correlation between the competition index and annual diameter increment for search radius $i$, and $\alpha$ and $\beta$ are parameters estimated using the NLIN procedure in SAS (SAS Institute Inc. 1996). The parameter $\alpha$ can be interpreted as an estimate of the maximum correlation and $\beta$ as an estimate of the OSR.

*Area overlap competition indexes*

The area overlap (AO) indexes were formally introduced by Opie (1968), but the most successful formulation was presented by Bella (1971) (equation (7)):

$$AO_i = \sum_{j=1}^{n_i}\left[\left(ZO_{ij}/Z_i\right)\left(D_j/D_i\right)^{EX}\right] \tag{7}$$

where: $AO_i$ is the AO index of Bella (1971) for tree $i$; $Z_i$ is the area of the 'zone of influence' of the subject tree $i$; $ZO_{ij}$ is the area of 'zone of influence' overlap between the subject $i$ and competitor $j$. $EX$ is the exponent applied to ratios, and previous studies (e.g. Bella 1971) have identified the optimal exponent as being between 1 and 3.

The AO indexes use a function of the area of overlap between a subject's and a competitor's 'zone of influence' to quantify competition. Their success depends on a suitable estimate of 'zone of influence', which is defined as the total area over which a tree obtains or competes for resources (Opie 1968). A prediction of crown area is used to quantify the zone of influence of each tree. Studies on the zone of influence

A large *Alstonia scholaris* (diameter at breast height = 133 cm) overtops the canopy of Danaru permanent sample plot (Photo: Julian Fox).

(e.g. Bi and Jurskis 1996) have found that the area over which a tree obtains or competes for resources is approximately equivalent to the area enclosed by two crown radii. A crown radius prediction for each tree in the PSP dataset was generated using the DCD allometric model described above.

*Area potentially available competition indexes*

The area potentially available (APA) indexes, first introduced in the forestry literature by Brown (1965), are derived from the classical Voronoi diagram, which is a continuous tessellation of an area into non-overlapping polygons. Brown (1965) introduced APA indexes to forestry as a means of quantifying the area potentially available for growth, and they have since been widely adopted as competition indexes. Several variants exist, including the weighted (APAW) and the weighted and constrained (APAWC). The APAW (Moore et al. 1973) weights the position of the perpendicular bisector on the line joining a tree to its competitor by a ratio of tree sizes. Nance et al. (1987) proposed the APAWC to curtail the development of large irregular polygons when spatial arrangements become irregular. When constructing the tessellation, they selected the smaller of the distance to the polygon boundary or the output of a constraining function. Nance et al. (1987) proposed the constraining function based on the predicted crown radius for the subject tree.

Three variants of the APA index are described in Table 3.

The APA class of competition indexes is the most complex to compute. A SAS macro (SAS Institute Inc. 1990) was written for efficient computation of all APA variants along with DWSR, AO and distance-independent indexes. SAS macros for quantifying the various competition indexes detailed in this study are available upon request from the primary author. An example of the APAWC for the Krisa PSP plot is shown in Figure 2. The spatial irregularity of the PSP plot can be observed.

*Alleviating boundary effects*

A boundary effect is generated when boundary trees are subject to competition from outside the plot that is not incorporated in competition indexes. To minimise information loss from exclusion of trees subject to edge effects, we used a toroidal edge correction scheme commonly used in spatial statistical applications (Ripley 1981). Toroidal edge correction is implemented by considering a rectangular spatial array as a torus. This can be realised simply by translating the spatial arrangement to create eight new adjoining arrays. The validity of toroidal edge correction depends upon the assumption that boundary trees are subject to equivalent competition from both outside and inside the plot; this is tenuous for trees close to the boundary (i.e. less than 5 m) in an irregularly structured tropical forest, but it should be permissible for trees more than 5 m from the boundary. Therefore, trees within 5 m of the boundary were excluded from analysis and toroidal edge correction was applied to all other trees.

*Distance-independent competition indexes*

Distance-independent indexes consist of functions of subject tree attributes compared with the attributes of other trees on the plot (Stage 1973). They do not use spatial information. The summed BA of trees within 20 m of the subject tree was quantified (BAS). The index developed by Stage (1973) was also quantified (equation (8)):

$$DAL_i = \sum_{i=1}^{n_i} D_i \tag{8}$$

**Table 3.** Area potentially available competition indexes

| Index | Weighting function | Constraining function | Author |
|---|---|---|---|
| *APA* | - | - | Brown (1965) |
| *APAW* | $DB_{ij} = \left[\frac{D_i^2}{(D_i^2 + D_j^2)}\right] Dis_{ij}$ | - | Moore et al. (1973) |
| *APAWC* | $DB_{ij} = \left[\frac{D_i^2}{(D_i^2 + D_j^2)}\right] Dis_{ij}$ | $CF_i = \sqrt{\frac{(PA \times (D_i / \sum_{j=1}^{t} D_j)}{\pi}}$ | Nance et al. (1987) |

Note:
$DB_{ij}$ = the distance to the perpendicular bisector located on the straight line between the subject $i$ and competitor $j$;
*APA* = area potentially available; *W* = weighted; *WC* = weighted and constrained.

*Evaluating competition indexes*

Competition indexes were evaluated for their ability to predict annual diameter increment in the next growing period using two criteria. The first criterion was the correlation between the index and the annual diameter increment in the next growing period. If the relationship between each variable and annual diameter increment was found to be nonlinear, a transformation was sought that rendered the relationship linear. In these instances the fit of the transformed variable was evaluated.

The second criterion was the significance of the competition index as a fixed effect in a mixed model with BA against annual diameter increment. BA was included as a fixed effect to extricate the influence of differing stand density on tree growth. A mixed model was used to account for the nested dependence (Fox et al. 2001) affecting PSPs; the growth of trees within each PSP will be more similar than that between the PSPs, as trees on the same plot will be subject to the same local environmental conditions, and will be of a similar forest type. To account for this, a random effect was used for each PSP measurement to ensure correct statistical inference on the growth and competition dynamics within and between PSP plots (Fox et al. 2001). After selecting an optimal competition index, individual tree growth (equation (9)) and mortality (equation (10)) models can be fitted.

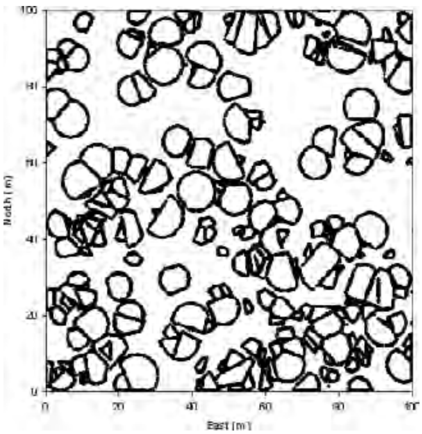

**Figure 2.** Graphic of the weighted and constrained area potentially available (APA) index for the Krisa permanent sample (PSP) plot

A secondary species, *Dendrocnide longifolia*, grows quickly to gain access to light on the Danaru permanent sample plot (Photo: Julian Fox).

### Individual-tree models

*HBM model fitting*

A conditional posterior for each parameter was obtained using a Gibbs sampler (Gelfand and Smith 1990) written in C++, and a non-informative flat prior (with large variance) was used for each parameter. We ran one MCMC of 20,000 iterations for each parameter, with a 'burn-in' period set to 10,000 iterations and the 'thinning' to 1/10. We then obtained 1,000 estimations for each parameter.

*Growth model*

$$\begin{aligned}
&\log(G_{ik}+2)=(\beta_0+b_{0,k})+(\beta_1+b_{1,k})\\
&\quad\log(D_i)+(\beta_2+b_{2,k})\log(C_i+1)+\varepsilon_i\\
&\varepsilon_i \sim \text{Normal}(0,V)\\
&[\beta_0,\beta_1,\beta_2]\sim \text{Normal}_3(0,V_\beta)\\
&[b_{0,\text{k}},b_{1,\text{k}},b_{2,\text{k}}]\sim \text{Normal}_3(0,V_b)\\
&V_b\sim \text{Inverse-Wishart}(r,rR)\\
&V\sim \text{Inverse-Gamma}(s_1,s_2)
\end{aligned} \tag{9}$$

where: $G_{ik}$ is the growth (mm/year) of tree $i$ of species $k$ between dates $t$ and $t+1$; $D_i$ is the diameter (cm) of tree $i$ at date $t$; $C_i$ is the competition index (m2/ha) in the neighbourhood of tree $i$ at date $t$; $\beta_0$, $\beta_1$, $\beta_2$ are global averages on the intercept, the slope of $D$ and the slope of $C$, respectively; $\beta_{0,\text{k}}$, $\beta_{1,\text{k}}$, $\beta_{2,\text{k}}$ are the species random effects on the intercept, the slope of $D$ and the slope of $C$, respectively.

*Mortality model*

$$\begin{aligned}
&S_{ik}\sim \text{Bernoulli}(\theta'_{ik})\\
&\theta'_{ik}=1-(1-\theta_{ik})^{Y_i}\\
&\text{logit}(\theta_{ik})=(\beta_0+b_{0,k})+(\beta_1+b_{1,k})\\
&\quad(D_i-20)+(\beta_2+b_{2,k})(C_i-20)+\varepsilon_i\\
&\varepsilon_i \sim \text{Normal}(0,V=1)\\
&[\beta_0,\beta_1,\beta_2]\sim \text{Normal}_3(0,V_\beta)\\
&[b_{0,\text{k}},b_{1,\text{k}},b_{2,\text{k}}]\sim \text{Normal}_3(0,V_b)\\
&V_b\sim \text{Inverse-Wishart}(r,rR)
\end{aligned} \tag{10}$$

where: $S_{ik}$ is the status (0 = alive, 1 = dead) of tree $i$ of species $k$ between dates $t$ and $t+1$; $Y_i$ is the time interval (years) between dates $t$ and $t+1$; $\theta'_{ik}$ is the mortality rate for time interval $Y_i$; $\theta_k$ is the annual mortality rate.

For the mortality model, we included in the expression of logit ($\theta_{ik}$) a residual error term $\varepsilon_i$ ~Normal(0,$V$) to account for overdispersion in the data (Hadfield 2010). We fixed V to 1. Using this parametrisation was convenient as it placed the estimation in the linear Gaussian regression framework and allowed us to use conjugated priors for parameters.

## Results

### Competition indexes

*Optimal competitor search radii*

Different trends in correlation across different search radii emerged for different species. An example of the fitted nonlinear model for Hegyi's (1974) index is shown in Figure 3. For *Pometia Pinnata*, $\alpha$ was estimated as 0.12 and $\beta$ as 13.7. These can be interpreted as an asymptotic correlation of 0.12 and an optimal search radius of 13.7 m.

Estimated OSRs for different species are detailed in Table 4. It can be observed that some species such as *Calophyllum* have small OSR values (3 m), while other species such as *Horsfieldia* have large OSR values (20 m). These results suggest that the range of the competitive effect is different among tropical species. For example, it could be hypothesised that *Calophyllum* is most affected by competition for light among immediate neighbours (competitors within 3 m) while, for *Horsfieldia*, competition for light and nutrients is more diffuse and occurs over a larger area (up to 20 m).

*Evaluating competition indexes*

Ten competition indexes were quantified for approximately 85,000 individual tree measurements across the 125 permanent sample plots. The 300 most numerous species on PSPs were selected for specific study of indexes. Preliminary analysis was used to identify a subset of indexes for further study. The best performing competition indexes were selected on the basis of strength of correlation with tree growth across the 300 species. The following subset was identified for further study:

- DBHOB (diameter at breast height over bark)
- BAS (sum of tree BA within 20 m of subject)
- SQAPAWC (square root of APAWC)
- LNNEW (natural logarithm of NEW)
- LNAO1 (natural logarithm of AO with exponent 1)

**Table 4.** Competition index performance and other statistics for the 16 most observed species on permanent sample plots

| Species | Sp code | Character | Obs | OSR | Optimal Corr | Corr | Optimal Mixed | Effect Sig | Wood Density | Diameter 90th quan | Mean Incr |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *Calophyllum* sp. | CAL SP | climax | 1,072 | 3.0 | BAS | –0.16 | BAS | 4.00E-03 | 0.50 | 47.0 | 0.53 |
| *Canarium* sp. | CAN SP | climax | 2,323 | 6.9 | BAS | –0.2 | BAS | 6.30E-08 | 0.48 | 36.5 | 0.42 |
| *Celtis* sp. | CEL | climax | 990 | 5.5 | LNNEW | –0.21 | BAS | 2.00E-04 | 0.55 | 50.0 | 0.52 |
| *Cryptocarya* sp. | CRY SP | climax | 1,993 | 7.4 | BAS | –0.09 | LNAO1 | 6.00E-02 | 0.46 | 34.7 | 0.44 |
| *Dysoxylum* sp. | DYS SP | climax | 1,846 | 14.2 | BAS | –0.2 | BAS | 3.00E-17 | 0.62 | 39.9 | 0.38 |
| *Ficus* sp. | FIC SP | climax | 1,536 | 5.9 | BAS | –0.2 | DBHOB | 2.90E-10 | 0.34 | 45.5 | 0.51 |
| *Garcinia* sp. | GAR SP | climax | 1,018 | 11.8 | LNNEW | –0.16 | LNNEW | 1.10E-04 | 0.64 | 31.5 | 0.37 |
| *Horsfieldia* sp. | HOR SP | climax | 1,682 | 20.0 | LNNEW | –0.14 | LNNEW | 1.30E-04 | 0.36 | 31.2 | 0.35 |
| *Litsea* sp. | LIT SP | climax | 1,022 | 5.7 | BAS | –0.25 | LNAO1 | 7.30E-11 | 0.40 | 38.4 | 0.51 |
| *Macaranga* sp. | MAC SP | pioneer | 1,426 | 14.3 | BAS | –0.27 | LNNEW | 9.50E-12 | 0.30 | 22.8 | 0.96 |
| *Myristica* sp. | MYR SP | climax | 3,113 | 9.6 | BAS | –0.16 | LNNEW | 1.40E-03 | 0.38 | 25.7 | 0.31 |
| *Pimeleodendron amboinicum* | PIM AMB | climax | 1,745 | 15.7 | LNNEW | –0.17 | DBHOB | 3.20E-07 | 0.48 | 39.8 | 0.42 |
| *Planchonella* sp. | PLA SP | climax | 1,683 | 9.0 | LNNEW | –0.21 | LNAO1 | 4.90E-09 | 0.45 | 37.6 | 0.44 |
| *Pometia pinnata* | POM SP | climax | 2,777 | 13.7 | LNAO1 | –0.16 | LNAO2 | 2.60E-10 | 0.58 | 54.4 | 0.67 |
| *Syzygium* sp. | SYZ SP | climax | 2,854 | 10.8 | BAS | –0.17 | BAS | 4.10E-12 | 0.61 | 41.1 | 0.37 |
| *Terminalia* sp. | TER SP | climax | 638 | 8.3 | BAS | –0.21 | LNAO1 | 3.40E-07 | 0.45 | 46.3 | 0.67 |

Note:
Obs is the number of observations; OSR is optimal search radius; Optimal Corr is the competition index with optimal correlation against annual diameter increment; Corr is the Spearman's correlation coefficient; Optimal Mixed is the competition index with optimal effect significance in a mixed model; Effect Sig is the t-test that the parameter is significantly different to zero; Wood density is basic density—the weight of wood (kg) at 0% moisture content occupying 1 $m^3$ from Eddowes (1977); Diameter 90th quan is the 90th quantile of the diameter distribution; and Mean Incr is the average annual diameter increment in the next growing period.

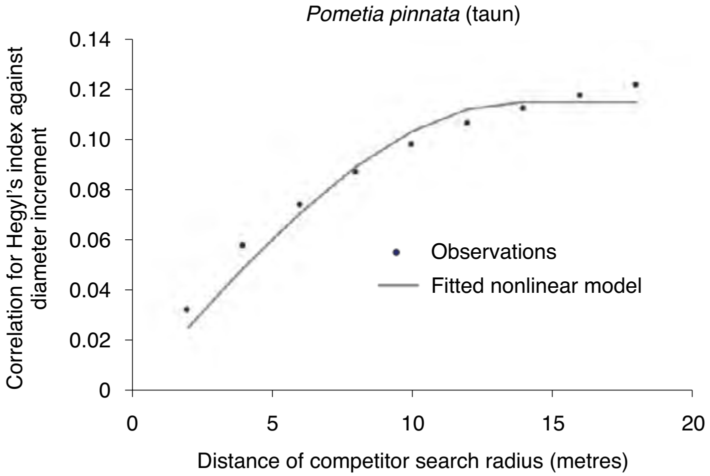


**Figure 3.** Fitted nonlinear model for estimating optimal competitor search radius for *Pometia pinnata*

The best performing competition index was then identified for each of the 300 species. Table 5 shows the indexes ranked for the percentage of the 300 species for which they were optimal (in terms of correlation with annual diameter increment). Table 5 also shows the indexes ranked for the number of times they were optimal in terms of fixed-effect significance in a mixed model with BA across the 300 species.

Table 5 demonstrates that no single competition index is optimal across the 300 species, and that distance-independent indexes such as DBHOB and BAS are equally as effective as distance-dependent indexes. BAS (28%, 21%) and LNNEW (29%, 29%) appear to be optimal most often across the 300 species. When BA was included as a fixed effect in a mixed model, distance-dependent indexes performed better (optimal for 61% of indexes). This may be due to total BA characterising stocking differences across PSPs and negating the influence of the distance-independent index, BAS (28% down to 21%).

Table 4 provides further detailed statistics of competition index performance for a subset of the 16 most observed species.

## Individual-tree models

Growth (equation (9)) and mortality (equation (10)) individual tree models were fitted to the PSP data with random species effects. Fitted models resulted in global average parameters ($\beta_0$, $\beta_1$, $\beta_2$) and species-specific parameters ($\beta_{0,k}$, $\beta_{1,k}$, $\beta_{2,k}$) describing growth and mortality processes for each species in equation (9) for growth and equation (10) for mortality for species *k*. The growth and mortality of individual trees was a function of tree size (diameter) and the local competitive environment (sum of BA within 20 m of subject). The global model with average parameters is shown in equation (11) for growth and equation (12) for mortality.

$$\log(G_{ik}+2)=(1.781+b_{0,k})+(0.055+b_{1,k})\log(D_i)+(-0.100+b_{2,k})\log(C_i+1) \quad (11)$$

$$\log(G_{ik}+2)=(1.781+b_{0,k})+(0.055+b_{1,k})\log(D_i)+(-0.100+b_{2,k})\log(C_i+1) \quad (12)$$

Global trends in growth and mortality against tree size ($D_i$) and competition ($C_i$) can be observed in equations (11) and (12). Growth increases with increasing tree size (positive parameter on $D_i$) but decreases with increasing competition (negative parameter on $C_i$). Both these observations are consistent with biological reality in tropical forests. The probability of mortality decreases with increasing tree size but increases with increasing competition (parameters in equation (12)). Again, these observations are consistent with biological reality.

Species-specific parameters such as $b_{1,k}$ in equations (11) and (12) allow each species to express its individual traits with respect to growth and mortality.

**Table 5.** Percentage of species for which each competition index was optimal

| Competition index | Correlation—percentage of species optimal | Mixed model—percentage of species optimal |
|---|---|---|
| DBHOB | 14 | 18 |
| BAS | 28 | 21 |
| SQAPAWC | 15 | 13 |
| LNNEW | 29 | 29 |
| LNAO1 | 14 | 19 |

Species-specific model parameters for the 16 most numerous species on PSPs, as well as predictions of growth and mortality for trees under conditions of low (10 $m^2$/ha) and high (50 $m^2$/ha) competition are shown in Table 6. All predictions are for medium-sized trees (40 cm dbh).

It can be observed that growth under low competition is always higher than under high competition, and this makes biological sense. Similarly, the probability of mortality under low competition is always lower than under high competition. For *Macaranga*, a pioneer species, the probability of mortality is twice as high under conditions of high competition relative to low competition.

## Discussion

Tropical forests are characterised by a high diversity of woody species, and no universally applicable species groupings exist that capture the continuum of growth, mortality and recruitment dynamics (Clark and Clark 1999). However, there is a need to group species for the development of forest growth models, as grouping similar species increases the sample size, thus reducing parameter variance, and may result in fewer and more frugal models that can be more easily applied in forest-management contexts. It is also important for the ecological insights it can offer on species growth habits. Ever since Whitmore (1975) first described tropical tree functional groups (fast-growing shade-intolerant pioneers, and slower growing shade-tolerant climax species), researchers have been attempting to group species using a variety of strategies, as reviewed by Gourlet-Fleury et al. (2005). Future work should explore if competition indexes can be used for species classification. For example, OSR values could be related to the shade-tolerance of different species. Species with small

Cultural immersion is likely to occur when undertaking forest assessment in remote areas of Papua New Guinea. Here, Heidi Zimmer is inducted as a ‘Simbu girl’ after spending time with the Kgwan community of Simbu province (Photo: Julian Fox).

**Table 6.** Growth and mortality parameters and example predictions for 16 most numerous species on permanent sample plots

| Species | Sp Code | Character | G-$b_0$ | G-$b_1$ | G-$b_2$ | M-$b_0$ | M-$b_1$ | M-$b_2$ | GLC | GHC | MLC | MHC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Calophyllum* sp. | CAL SP | climax | 1.514 | 0.171 | –0.093 | –3.203 | –0.003 | –0.024 | 3.425 | 3.100 | 0.018 | 0.047 |
| *Canarium* sp. | CAN SP | climax | 1.501 | 0.106 | –0.074 | –3.539 | –0.005 | –0.016 | 2.919 | 2.683 | 0.016 | 0.030 |
| *Celtis* sp. | CEL SP | climax | 2.484 | –0.025 | –0.221 | –3.895 | –0.007 | –0.014 | 7.158 | 5.905 | 0.012 | 0.020 |
| *Cryptocarya* sp. | CRY SP | climax | 1.610 | 0.071 | –0.068 | –3.300 | 0.014 | –0.010 | 3.218 | 2.986 | 0.034 | 0.051 |
| *Dysoxylum* sp. | DYS SP | climax | 1.261 | 0.190 | –0.098 | –3.904 | 0.003 | –0.010 | 2.321 | 2.049 | 0.016 | 0.023 |
| *Ficus* sp. | FIC SP | climax | 1.786 | 0.094 | –0.134 | –3.362 | –0.006 | –0.017 | 4.029 | 3.513 | 0.018 | 0.035 |
| *Garcinia* sp. | GAR SP | climax | 1.771 | 0.074 | –0.149 | –3.392 | 0.003 | –0.019 | 3.664 | 3.129 | 0.020 | 0.041 |
| *Horsfieldia* sp. | HOR SP | climax | 1.543 | 0.025 | –0.042 | –3.990 | 0.018 | –0.004 | 2.664 | 2.537 | 0.023 | 0.027 |
| *Litsea* sp. | LIT SP | climax | 1.728 | 0.138 | –0.142 | –3.428 | 0.013 | –0.006 | 4.058 | 3.512 | 0.034 | 0.042 |
| *Macaranga* sp. | MAC SP | pioneer | 2.482 | 0.002 | –0.163 | –2.712 | 0.000 | 0.018 | 8.133 | 7.089 | 0.052 | 0.102 |
| *Myristica* sp. | MYR SP | climax | 1.591 | 0.045 | –0.086 | –3.873 | 0.017 | –0.005 | 2.827 | 2.559 | 0.024 | 0.030 |
| *Pimeleodendron amboinicum* | PIM AMB | climax | 2.631 | –0.230 | –0.091 | –4.139 | 0.027 | –0.027 | 6.736 | 6.223 | 0.012 | 0.035 |
| *Planchonella* sp. | PLA SP | climax | 1.565 | 0.132 | –0.107 | –3.544 | 0.013 | –0.008 | 3.289 | 2.925 | 0.029 | 0.039 |
| *Pometia pinnata* | POM SP | climax | 1.493 | 0.109 | –0.111 | –3.663 | 0.007 | –0.051 | 2.720 | 2.382 | 0.006 | 0.047 |
| *Syzygium* sp. | SYZ SP | climax | 1.636 | 0.057 | –0.102 | –3.564 | 0.006 | –0.021 | 3.060 | 2.728 | 0.017 | 0.038 |
| *Terminalia* sp. | TER SP | climax | 1.889 | 0.073 | –0.083 | –3.814 | 0.019 | –0.002 | 4.824 | 4.459 | 0.030 | 0.032 |

Note:
G-$b_0$, G-$b_1$, G-$b_2$ are parameters for the growth model (9), while M-$b_0$, M-$b_1$, M-$b_2$ are parameters for the mortality model (10). GLC, GHC, MLC, MHC are growth (cm/year) under low competition (10 $m^2$/ha), growth under high competition (50 $m^2$/ha), probability of mortality (between 0 and 1) under low competition, and probability of mortality under high competition, respectively.

OSR values that are most affected by competition for light would be expected to be shade intolerant, while species with large OSR with a more diffuse competitive affect would be shade tolerant.

Table 4 also provides insights into tree attributes that could be used as a basis for species grouping. Wood density, growth rate and potential size have been used in other studies to group species. *Macaranga* is a pioneer species with the largest growth rate (0.96 cm/year), smallest potential size (22.8 cm), lowest wood density (300 kg/m$^3$) and strongest correlation for competition indexes (0.27). This is congruent with previous findings that pioneer species tend to be fast growing, have small potential size and low wood density, and tend to be shade intolerant with a life cycle characterised by rapid growth to capitalise on canopy gaps. Intolerance to shade from nearby trees confirms the importance of competition indexes in explaining future growth. In contrast, *Pometia pinnata* (taun) is a climax species with a slower growth rate (0.67 cm/year), large potential size (54.5 cm), denser wood (580 kg/m$^3$) and weaker correlation for competition indexes (0.16). Again, this is congruent with climax species being slower growing, having larger potential size and denser wood, and being more tolerant of shade from nearby trees. More tolerance to competition explains the weaker correlation of competition indexes with future growth. The local spatial arrangement of soil fertility and topographic, geologic and climatic factors will be more important in explaining growth for shade-tolerant species. Other species in Table 4 fall on the continuum between pioneers such as *Macaranga* and climax species such as *Pometia pinnata*. This suggests that competition response, as characterised by competition indexes, could be used as an additional attribute for species groupings in tropical forests.

This analysis suggested that no single competition index is dominant, with indexes BAS and LNNEW performing well. The optimal index for each species explained only a modest amount (14–27%) of the variability in diameter increment. However, indexes were highly significant when evaluated in a mixed model with BA/ha. Failure to identify a single index as optimal in the mixed tropical forests of PNG could be associated with variability in competition response across the 300 species. Shade-intolerant species will compete strongly with first-order neighbours for light and nutrients. The SQAPAWC most accurately characterises these first-order interactions. The LNAO1 and LNNEW competition indexes may perform better for more shade-tolerant species, as competition for light and nutrients would be more diffuse, less intense, and would occur over a larger area. Following this hypothesis, distance-independent indexes such as BAS and DBHOB would perform well for very shade-tolerant species for which the location and size of nearby competitors is relatively unimportant. Future work should attempt to align the shade tolerance of different species with the performance of different competition indexes.

Diameter performed well as a predictor of growth—better than competition indexes for 14% and 18% of species. This is in agreement with previous studies (Lorimer 1983). Diameter can be considered a historical log of past competitive interactions, genotypic differences and localised environmental heterogeneity, and therefore tends to be strongly correlated with future growth.

Tree growth is a complex process. It is influenced by an intricate network of above- and below-ground competitive interactions as well as the local spatial arrangement of soil fertility and topographic, geologic and climatic factors. The vast majority of current competition indexes and growth models remain overly simplified (Fox et al. 2001). This results in large amounts of unexplained variability, and growth modellers have come to accept this as an 'occupational hazard' (Burkhart and Gregoire 1994). Competition indexes explained, at best, 25% of the variability in individual tree growth in mixed tropical forest in PNG. Future work requires insights into this unexplained variability that can improve growth model performance. Despite these shortcomings, the competition indexes examined here, and the insights into competitive dynamics they provided, can guide further growth model development for mixed tropical forest in PNG.

Work described in this paper represents an initial investigation of competition index selection in tropical forests, and application of individual-tree-based models with demographic hierarchical Bayesian models, including species random effects. Results suggest that the approach shows promise. Future work should fit a recruitment model and use species-specific competition indexes in growth/mortality models.

The forest assessment tool is described elsewhere and is based on a stratified random variable-radius plot inventory (Fox et al. 2011b). The assessment tool incorporates lookup tables that facilitate the calculation of plot- and estate-level above-ground live biomass (t/ha) and merchantable volume ($m^3$/ha). In future work this forest assessment tool can used as a basis for the individual-tree growth and yield module, which can then be used to simulate forest development into the future. Data from the forest assessment tool can be read into the forest simulation tool, which is under development at <http://twoe.org>. Using individual-tree HBM model parameters estimated from the PSPs, assessment data can be used as the basis of a simulation. Lookup tables for species-specific HBM parameters for growth, mortality and recruitment models are available from the primary author. Each tree measured in the assessment therefore becomes a tree in the simulation that is subject to perturbations from growth and possible mortality into the future. New trees eventuate in the simulation from the recruitment model that uses tree density and species present on each plot to create a probability of recruitment.

A simple tree-level simulator housed in accessible software (http://twoe.org) can assist community-level decision-making with regards to the design and intensity of selective-harvesting regimes. For example, after the forest assessment is complete, a simulation of a harvesting event can be implemented with different size limits, cutting intensities and species. For community forest management, this will allow communities to maximise returns from harvesting while preserving other forest values. Small-scale, high-value utilisation scenarios can be effectively explored using such models. Utilisation below unsustainable levels, which has been set in the simulator according to species-specific growth rates, will ensure that high-end products can be harvested in community areas in perpetuity.

PNGFA is moving to a new preharvest inventory method based on a stratified random variable-radius plot inventory that will replace the 1% stripline inventory, which is both inefficient and biased. Therefore, PNGFA can populate the assessment tool with inventory information and run scenarios for large-scale harvesting using software available at <http://twoe.org>. The scenarios can help identify appropriate and sustainable harvesting in terms of size limits, species mixes and cutting cycles. Currently, a default size limit of 50 cm is used on a 35-year cutting cycle. It is intended that the assessment and modelling tools developed as part of ACIAR project FST/2004/061 can help refine this approach for more sustainable forest harvesting.

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# Dendrochronology as a tool for understanding forest growth in Papua New Guinea's montane forests

**Heidi C. Zimmer[1,2]* and Julian C. Fox[1]**

*Abstract*

Tree rings, where they are present, can provide insight into the complexities of tropical forest dynamics. The forests of Papua New Guinea (PNG) exist across a wide range of climates and environments. In particular, the climate of some highland areas is characterised by seasonal rainfall and temperature variation—unusual for near-equatorial latitudes. We hypothesised that these conditions would be growth limiting for trees and promote the formation of annual tree rings. An exploratory dendrochronological study was undertaken in the montane forests of Simbu province, PNG. The wood anatomy of 13 tree species was investigated—six species had clear tree rings. Using dendrochronological data, annual growth rates and carbon sequestration of *Nothofagus grandis* and *Podocarpus crassigemmis* were reconstructed. Potential drivers of variation in annual growth, such as climate and disturbance, are discussed. This study highlights the many opportunities for further dendrochronological research in PNG.

## Introduction

### Challenges and opportunities in tropical tree rings

Dynamics research into tropical forest stands poses a challenge because tropical forests are typically structurally complex and highly species rich. Forest-stand dynamics are defined as the changes in forest-stand structure (i.e. species composition, age structure and biomass) with time, including stand development after disturbance (Oliver and Larson 1996). Dendrochronology (the study of tree rings), the tool most commonly used in stand dynamics studies, is of limited utility in tropical forests as few tropical tree species produce annual growth rings (Baker et al. 2005). This is because temperature, the limiting factor for growth in temperate regions, is relatively constant in the tropics. Nevertheless, several recent tropical forest studies incorporating dendrochronology have resulted in advances in our understanding of tropical forest stand dynamics (e.g. Baker et al. 2005; Baker and Bunyachewin 2006; Buckley et al. 2007; Couralet et al. 2010; Rozendaal et al. 2010). Recent progress in tropical forest stand dynamics research, alongside emergence of a market for forest carbon (C), has resulted in increased interest in understanding the dynamics of Papua New Guinea's (PNG's) forests.

### Why Papua New Guinea?

The island of New Guinea encapsulates the world's third largest tropical rainforest, shared between PNG and the Indonesian province of Irian Jaya. Exceptional diversity in climate, altitude and drainage conditions (Paijmans 1976), as well as its position at an important biological transition zone—Wallace's and other demarcation lines (van Balgooy

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1972)—contribute to PNG holding more than 5% of global biodiversity on less than 1% of the world's land area (Heads 2001, cited in Haberle 2007). Exceptionally high species richness and endemism have led to PNG's designation as one of the world's 'mega-diverse' countries (Mittermeier et al. 2003).

Although a large proportion of PNG's forests are defined as primary, their history has not been free from disturbance; for example, drought, fire and frost (Johns 1989). Disturbances are a fundamental driver of the stand dynamics of all forests (Oliver and Larson 1996), initiating mortality and recruitment, and modifying forest structure, composition, flammability and C content (Nepstad et al. 2007). Droughts are among the major drivers of 'natural' disturbance in PNG's forests, generally coinciding with the El Niño Southern Oscillation (ENSO).

The impacts of drought on forests are multiple. In PNG they can result in fires and are associated with frosts at higher elevations. At the plant scale, moisture stress can limit photosynthesis, decrease annual growth, and cause plant dieback and mortality. Drought impacts composition, and hence forest dynamics, through among-species variation in resilience and response to water stress (Newberry and Lingenfelder 2009). In a regional-scale study of the Amazon, Phillips et al. (2009) found that biomass losses were driven by both infrequent large increases in mortality (particularly of fast-growing, light-wooded species) and small, but widespread, decreases in growth. The greatest drought-induced biomass losses were recorded at sites where mean annual rainfall was highest and climate was typically aseasonal. If the trends in the Amazon are indicative of trends in other tropical forests, the impact of drought on forests in PNG may favour the growth and survival of particular species over others, and have a greater impact where rainfall is higher and more aseasonal.

Tree mortality and dieback increase forest susceptibility to fire. Historical accounts of widespread rainforest fire in PNG have been correlated with the ENSO and consequent drought (Johns 1989). Fire can create a feedback loop, where fire-induced mortality further increases the fire risk—each tree that dies, or dies back, contributes to warming and drying of the forest interior, thus increasing fire risk (Uhl and Kaufmann 1990; Nepstad et al. 1999; Cochrane 2003).

Severe ENSO-induced droughts in PNG coincide with cool temperatures, which are typified by frosts in the highlands (Brookfield and Allen 1989). Frosts occur because of a breakdown in convection currents, resulting in subsidence, where cool air sinks and condenses (Brookfield and Allen 1989). Frosts can cause dieback or mortality in trees (especially young trees or those at forest edges), thus maintaining treeless open grasslands in PNG's highlands (Smith 1975; Brookfield and Allen 1989).

### Potential for tree rings in the montane forests of Papua New Guinea

In the highlands of PNG seasonal variations in rainfall and frost occurrence (>2,700 m) are known to occur (McAlpine et al. 1983; Barr 1998), and may serve to regulate growth and create annual growth rings (Worbes 1995). Numerous tree families known to produce tree rings elsewhere occur in montane forests of PNG; for example, Cunoniaceae, Coniferae, Nothofagaceae, Podocarpaceae and Rutaceae (Dunwiddie 1979; Duncan 1989; Villalba and Veblen 1997; Guiterrez et al. 2004; Brienen et al. 2009). Ash (1988), in a dendrochronological study of *Nothofagus* spp. on Mt Giluwe in the highlands of PNG, found regular growth rings of parenchyma, and confirmed annual growth with radiocarbon dating.

For our study we asked:

1. Are there tree species in PNG's montane forests that produce anatomically distinct, reliable annual tree rings that would cross-date within and between trees? If yes:
2. What is the historical variation in annual growth, and therefore carbon sequestration, of these trees?

## Methods

### Study area

We conducted fieldwork in three montane forests of Simbu province, PNG (Figure 1), in September 2009. Montane forest was chosen because it was most likely to experience rainfall and temperature seasonality, and include taxa known for their dendrochronological potential, and because it was close to permanent sample plots (PSPs) providing complementary data on tree growth and mortality.

*1. KGWan*

The KGWan forest area is located in the Gembogl district (Mitnande local-level government) in Simbu province. It incorporates large areas of primary (upper and lower mixed evergreen) montane rainforest from 2,750 to 3,500 m altitude. The forest area extends to Asaro in the Eastern Highlands province.

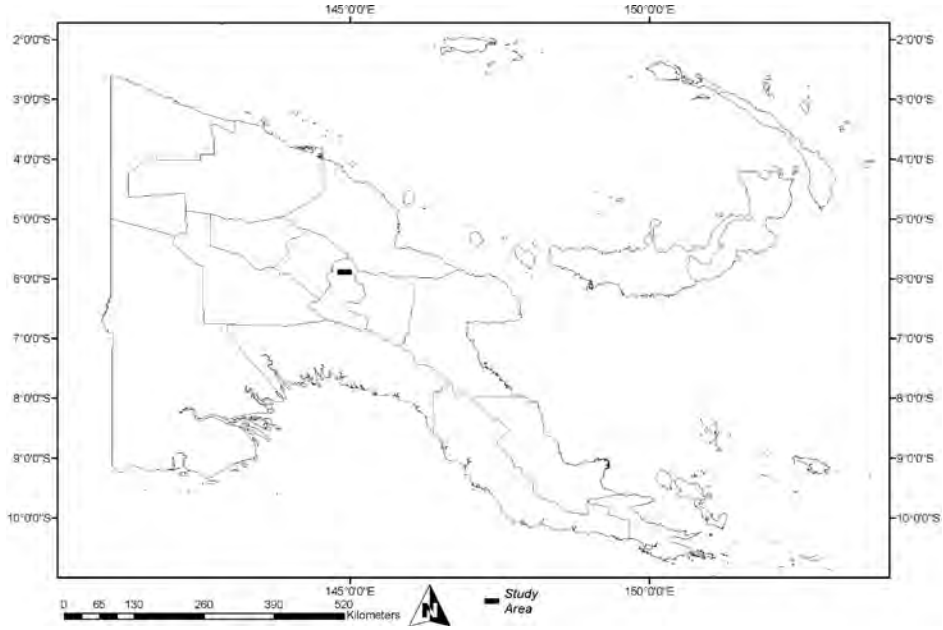


**Figure 1.** Map of Papua New Guinea showing the location of the study area in Simbu province

Two 1-ha permanent sample plots at approximately 2,800 m have been established in mixed evergreen montane forest and *Nothofagus grandis* dominated forest (Figure 2) as part of Australian Centre for International Agricultural Research (ACIAR) project FST/2004/061 (Fox et al. 2010).

*2. Mt Wilhelm and Pindaunde Valley*

At 4,509 m, Mt Wilhelm is the highest peak in PNG. The Pindaunde Valley (Figure 3) lies on the eastern flank of Mt Wilhelm and consists of three levels, the upper two levels dominated by rock basin lakes. The topography of the valley was formed largely by glacial processes (Corlett 1984). The climate is wet and cold, with mean daily temperatures between 4.0 and 11.6 °C (Pindaunde Field station, cited in Corlett 1984), and annual rainfall ~5,000 mm (McAlpine et al. 1983). The vegetation of the subalpine zone—from 3,300 m to the tree line at 3,900–4,000 m—is a mosaic of upper montane forest, grassland and bogs (Paijmans 1976; Corlett 1984). *Dacrycarpus compactus* dominates the forest fragments with several other species. Smith (1975) suggests that *D. compactus* (krummholz) individuals beyond the tree line indicate the forests' relictual distribution. The majority of grasslands in the Pindaunde Valley are thought to be secondary, caused by anthropogenic burning (Corlett 1984).

*3. Kuraglumba*

Kuraglumba is an intermontane basin containing a grassland area approximately 3 km wide and 8 km long, and ranging in altitude from 2,730 m to 2,850 m (Figure 4). According to Smith (1975), the majority of the grassland at Kuraglumba was initiated, and then maintained and expanded, by anthropogenic burning, as it lies on an important and well-used track from the upper Simbu Valley to Goroka. Frost is unlikely to have caused the forest retreat at Kuraglumba, but it may maintain the grassland by limiting forest regeneration (Smith 1975). However, treelessness towards the floor of depressions (inverted tree lines) may well have occurred naturally, before expansion by anthropogenic burning, as very wet bog-type vegetation or frost hollows. The forest surrounding Kuraglumba is evergreen mixed lower montane forest and coniferous forest dominated by *Podocarpus crassigemmis* (Figure 5). On slopes it is typical for coniferous forest to form a belt or transition zone between the grassland below and mixed forest above (Paijmans 1976); this was the case at Kuraglumba.

**Figure 2.** Photograph taken in the *Nothofagus grandis* dominated forest within the KGwan forest area (Photo: Heidi Zimmer).

**Figure 3.** Tree cores being collected at 3,500 m above sea level within the Pindaunde Valley on the slopes of Mt Wilhelm (Photo: Julian Fox).

**Figure 4.** Photo taken at Kuraglumba grassland showing stream and tree line (Photo: Heidi Zimmer).

**Figure 5.** Tree core being collected from *Podocarpus crassigemmis* by Yeppa on Kuraglumba grassland (Photo: Julian Fox).

*Climate*

The climate of PNG is tropical, as a result of its position between 2 and 12 degrees south of the equator. Nevertheless, the climate is strongly influenced by seasonal variations of the major equatorial circulation patterns. During the cool season (May–October), the climate is characterised by tropical easterly air flows and generally lower rainfall; during the austral summer monsoon (December–February), equatorial north-westerlies are dominant, bringing higher rainfall (McAlpine et al. 1983; Haberle 2007). The Southern Oscillation is an important driver of circulation patterns over the region. Negative records of the Southern Oscillation Index and ENSO warm events correspond to drought in PNG (Barr 1998).

Rainfall regimes are highly variable across PNG due to interactions between local and regional circulation patterns, disturbances, and the altitude and alignment of the island's physiography (McAlpine et al. 1983). Over most of the island, mean annual rainfall is 2,000–4,000 mm, although in places mean annual rainfall can reach 10,000 mm. In some areas rainfall increases with altitude while in others it does not. In the upper Simbu Valley this relationship is seasonal, with increased rainfall at altitude only in the wet season (Barry 1978, cited in Brookfield and Allen 1989). Rainfall is seasonal across most of the island, although the dry season may merely be 'less wet' (e.g. 300 mm mean monthly rainfall in the wet season compared with 100–150 mm in the dry). Periods of more than 4 four rainless days are uncommon except in the driest areas; for example, Port Moresby, Madang, Goroka and Mt Hagen, where periods of 10–20 rainless days may occur. Further, the wet season may occur between January and April (the north-west season) or May and August (the south-east season), the latter occurring in regions with mountains running north-east/south-west, blocking in the south-east trade winds.

Variability in annual rainfall totals shows little or no correlation among stations (i.e. drought years and flood years may only be localised (McAlpine et al. 1983)). In terms of temperature, the lowlands of PNG are generally warm year round, with daily averages decreasing by several degrees during May–October. However, temperatures in the highlands are much cooler and frosts may occur above 2,700 m during May–October (Barr 1998).

In the highlands two sources of seasonal, growth-limiting variation in climate are possible. First, high-elevation areas in the tropics may experience low temperatures, including frosts. In PNG, upper montane temperatures decline to annual mean minima of 4 °C (and annual mean maxima of 11 °C), with frosts occurring on 50% of days; a cooler season during May–October has been identified by McAlpine et al. (1983) and Barr (1998). Second, PNG generally experiences its lowest rainfalls during the austral winter (June–August). Some highland weather station records display well-defined annual dry seasons; for example, those for Goroka (Allen et al. 1989).

## Sampling design

The production of annual tree rings relies both upon tree physiology and the presence of climatic conditions that are seasonally limiting to growth. In this study, sample sites were chosen, where possible, in areas experiencing the greatest climatic extremes; for example, ridges, tree lines and inverted tree lines.

Two sampling approaches were taken. First, trees from families of known dendrochronological potential were randomly selected for sampling when they were abundant; otherwise, all individuals that could be located were sampled—at least 15 trees per site for species with visible growth rings. In addition, species that occurred less commonly in the mixed species forests were sampled when encountered, resulting in one or two trees sampled per species. Tree location was recorded using GPS, so that the location of individual trees within the stand could be mapped. Increment borers (Haglof, Sweden; Suunto, Finland) were used to remove one to two samples per tree at breast height, depending on tree size, with the objective of capturing at least two tree-ring chronologies from bark to pith. Core samples were sealed into straws. Where possible, four cores were taken, to increase the likelihood of capturing each tree ring on at least one core (Duncan 1989), and old injuries and buttresses were avoided. Samples were prepared in the laboratory using standard dendrochronological methods—samples were glued to mounts, sanded with increasingly fine grits (180–800) of sandpaper (Stokes and Smiley 1968), and then scanned at high resolution (1,800 dpi) using a Scanmaker 1000XL scanner (Microtek International Inc.).

## Chronology development

Visual cross-dating was undertaken with Windendro (Regent Instruments Inc., Canada) image analysis software. Species lacking the potential for statistical cross-dating were omitted from further analysis (e.g. earlywood and latewood not clearly defined; no correspondence in tree-ring patterns between samples taken from the same tree (Stokes and Smiley 1968)). COFECHA was used for statistical cross-dating—COFECHA is a program that calculates cross-correlations (mean inter-series correlations) between each individual ring-width series and a mean chronology (Holmes 1983). Mean chronologies were generated from all the ring-width series at a site (Grissino-Mayer 2001). Some individual ring-width series showed irregular growth patterns and/or unclear ring structure, and correlated poorly with the mean chronology. These series were rechecked and either corrected or removed from further analysis. This allowed us to reduce the effects of random growth caused by local disturbances that were recorded only in individual trees (Grissino-Mayer 2001). For species that could be cross-dated, a subset of ring-width series with high average inter-series correlation was used to create a master chronology with the objective of representing a stand-level growth signal (data not presented here).

*Tree age estimation*

If the core did not intersect the pith, the missing distance to the pith was estimated using Duncan's (1989) geometric method (equation (1)).

$$r = (L^2/8h) + (h/2) \quad (1)$$

where: $r$ is the length of the missing radius (between end of core and pith); $h$ and $l$ are the height and length of the centre-most (visible) tree ring (Duncan 1989).

The estimated distance to the pith was then divided by the average ring width of the five rings closest to the pith (Duncan 1989), providing the number of missing years between the last ring on the core and the missed pith.

*Annual growth rate and carbon estimation*

Tree-ring (annual growth) data were used to reconstruct annual change in stem diameter. Annual growth for each tree was estimated by averaging the growth of two to four core samples. Above-ground biomass, for each tree in each year, was estimated using the allometric model (equation (2)) developed by Chave et al. for wet tropical forests (Chave et al. 2005; Fox et al. 2010):

$$AGLB_i = 0.0776\,(p_i D^2_i H_i)^{0.940} \quad (2)$$

where: $AGLB_i$ is above-ground live biomass; $D_i$ is the diameter (cm); $H_i$ is the total height (m); $p_i$ is the wood specific gravity (g/cm$^3$) for tree $i$.

Species-specific height–diameter models were drawn from PNG's PSP data (Fox et al. 2010), with species-specific or genus-mean wood density values from Eddowes (1977). The resulting $AGLB_i$ is the total biomass of the stem, crown and leaves for tree $i$ (in kg) (Chave et al. 2005). The C fraction of biomass is assumed to be 50% (Clark et al. 2001; Houghton et al. 2001; Malhi et al. 2004). This model was also used by Fox et al. (2010) to estimate AGLB for PNG's PSP network.

# Results

## Dendrochronological viability analysis

A total of 96 individuals from 13 tree species was sampled, and ~10,000 tree rings were measured. Four species sampled intensively (30–60 cores) were: *Nothofagus grandis* (Nothofagaceae) from KGWan, *Papuacedrus papuanus* (Cupressaceae) and *Podocarpus crassigemmis* (Podocarpaceae) from Kuraglumba, and *Dacrycarpus compactus* (Podocarpaceae) from Mt Wilhelm (Figure 6a–d). *Nothofagus grandis* had regular bands of parenchyma although there was little differentiation in vessel size. Samples taken from different radii on the same tree were successfully cross-dated (Figure 7). A chronology of annual growth was reconstructed for each *N. grandis* individual, providing a historical record of growth of up to 175 years. Analysis of samples at the stand scale also revealed potential for cross-dating among trees (Figure 8).

Despite successful dendrochronological analysis of other species from the family Cupressaceae (e.g. *Libocedrus* spp.; D'Arrigo et al. 2000; Xiong and Palmer 2000), the tree rings of *Papuacedrus papuanus* could not be cross-dated. The wood anatomy of *Dacrycarpus compactus,* from the family Podocarpaceae, sampled from > 3,000 m elevation on the slopes of Mt Wilhelm, also did not reveal clear rings. *Dacrycarpus dacryoide*s has been the subject of dendrochronological studies in New Zealand (Duncan 1989; Wells et al. 2001).

The tree rings of *Podocarpus crassigemmis* were distinct and characterised by a clear boundary between the small, dark-coloured tracheids of latewood and the large, light-coloured earlywood tracheids. Samples could be cross-dated within single trees (Figure 9), but cross-dating among and between trees was generally difficult (although see Figure 10).

Of the nine species opportunistically sampled, four were identified as having the potential for further sampling and analysis (Table 1; Figure 6e–h). *Cryptocaria* cf. *ledermannii* had clear bands of parenchyma; *Elaeocarpus culminocola* similarly had clear bands of parenchyma and displayed some variation in vessel size; and *Dacrydium nidulum* showed a clear boundary between latewood and earlywood tracheids; while the visibility of parenchyma bands in *Prunus* cf. *grisea* varied among individuals sampled.

## Annual growth, carbon sequestration and storage

Annual diameter increase in *Nothofagus grandis*, reconstructed from tree rings, varied from < 0.01–3.01 cm/year (mean = 0.4 cm/year). The trees surveyed had a mean C storage of 1,022.5 kg per tree (mean [field measured] dbh = 50.48 cm,

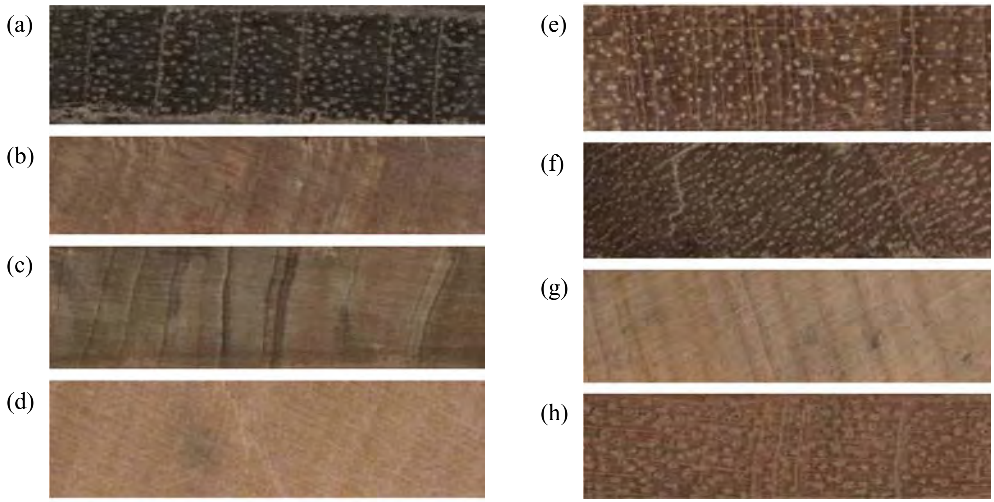


**Figure 6.** Increment samples: (a) *Nothofagus grandis*, (b) *Papuacedrus papuanus*, (c) *Podocarpus crassigemmis,* (d) *Dacrycarpus compactus,* (e) *Cryptocarya* cf. *ledermannii,* (f) *Elaeocarpus culminocola,* (g) *Dacrydium nidulum* and (h) *Prunus* cf. *grisea.*

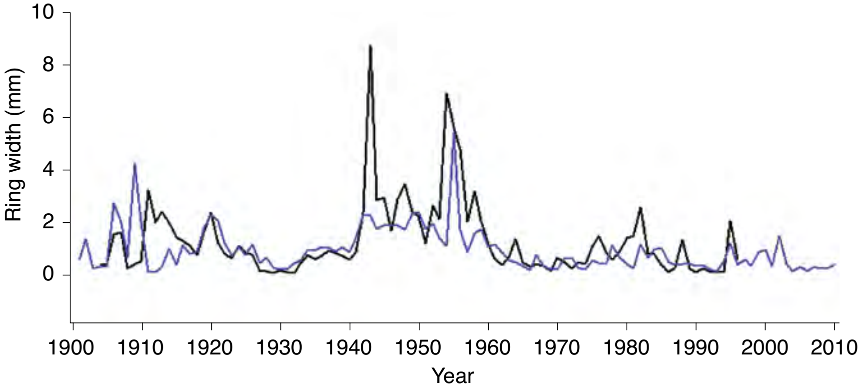


**Figure 7.** Two series of ring-width measurements from a single *Nothofagus grandis* tree, demonstrating the ability to match, or cross-date, such measurements within a tree

wood density = 0.64g/cm$^3$). The oldest *N. grandis* was 177 years old and stored an estimated 818 kg of C at time of sampling (Figure 11) (reconstructed dbh [45.7 cm] was slightly higher than field-measured dbh [43.2 cm]). The historical C sequestration for this tree, determined from tree-ring reconstructed annual variation diameter growth, averaged 4.7 kg/year, although this was highly variable, ranging from < 0.01 kg/year early in the chronology to 25.5 kg/year later in the chronology.

The *Podocarpus crassigemmis* trees were generally smaller and slower growing than the *Nothofagus grandis*. For *P. crassigemmis,* annual increase in diameter varied from < 0.01–1.3 cm/year (mean = 0.3 cm/year). *P. crassigemmis* had a mean C storage of 217 kg per tree (mean [field measured]

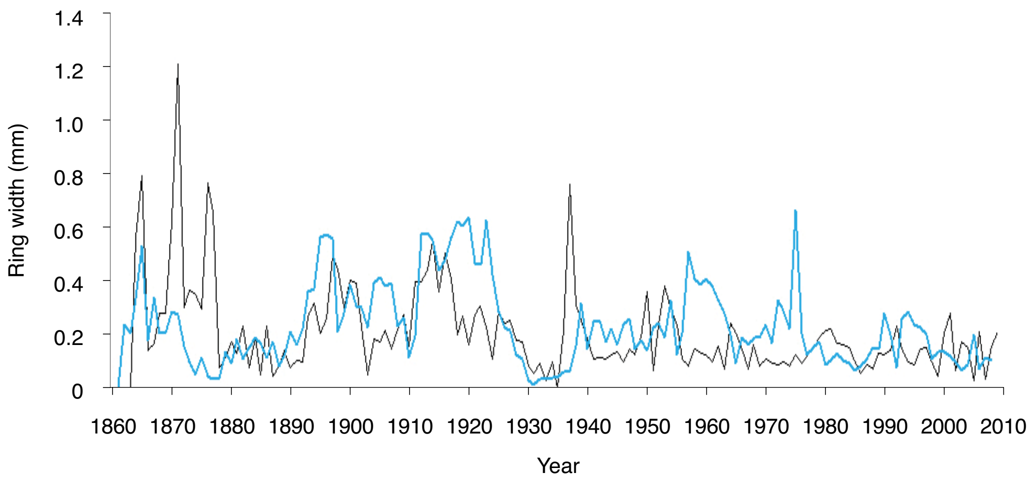


**Figure 8.** Ring-width measurements from two *Nothofagus grandis* trees, showing the potential to match, or cross-date, such measurements among trees

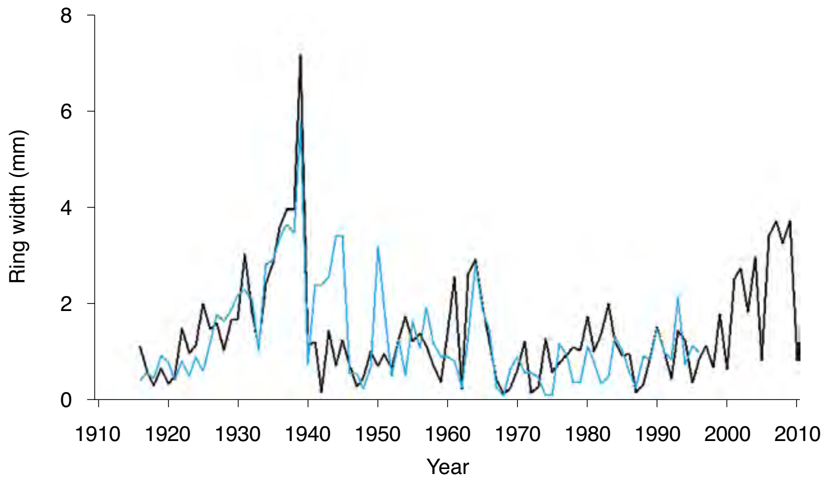


**Figure 9.** Two series of ring-width measurements from a single *Podocarpus crassigemmis* tree, demonstrating the ability to match, or cross-date, such measurements within a tree

dbh = 28.1 cm, wood density = 0.51 g/cm³). The oldest *P. crassigemmis* was 134 years old and stored an estimated 319 kg of C at time of sampling (Figure 12) (reconstructed dbh [36.6 cm] was slightly higher than field-measured dbh [36.4 cm]). Carbon sequestration averaged 3.2 kg/year and was highly variable, ranging from < 0.01 kg/year early in the chronology to 16.6 kg/year later in the chronology.

**Table 1.** PNG tree species sampled; their potential for dendrochronological analysis was assessed—species that warrant further investigation are highlighted with an asterisk.

| Species | Family | Location |
|---|---|---|
| *Acronychia pullei** | Rutaceae | KGWan |
| *Cryptocaria* cf. *ledermannii** | Lauraceae | KGWan |
| *Dacrycarpus compactus* | Podocarpaceae | Mt Wilhelm |
| *Dacrydium nidulum** | Podocarpaceae | KGWan |
| *Elaeocarpus* cf. *murukkai* | Elaeocarpaceae | KGWan |
| *Elaeocarpus culminocola* | Elaeocarpaceae | KGWan |
| *Fagraea* sp.* | Gentianaceae | Kuraglumba |
| *Litsea firma* | Lauraceae | KGWan |
| *Nothofagus grandis** | Fagaceae | KGWan |
| *Nothofagus pullei** | Fagaceae | KGWan |
| *Papuacedrus papuanus* | Cupressaceae | Kuraglumba |
| *Podocarpus crassigemmis** | Podocarpaceae | Kuraglumba |
| *Prunus* cf. *grisea* | Rosaceae | KGWan |
| *Quintinia montis-wilhelmi* | Grossulariaceae | Mt Wilhelm |
| *Schizomeria serrata* | Cunoniaceae | KGWan |
| *Sericolea decandra* | Elaeocarpaceae | KGWan |
| *Vaccinium* sp. | Ericaceae | Mt Wilhelm |

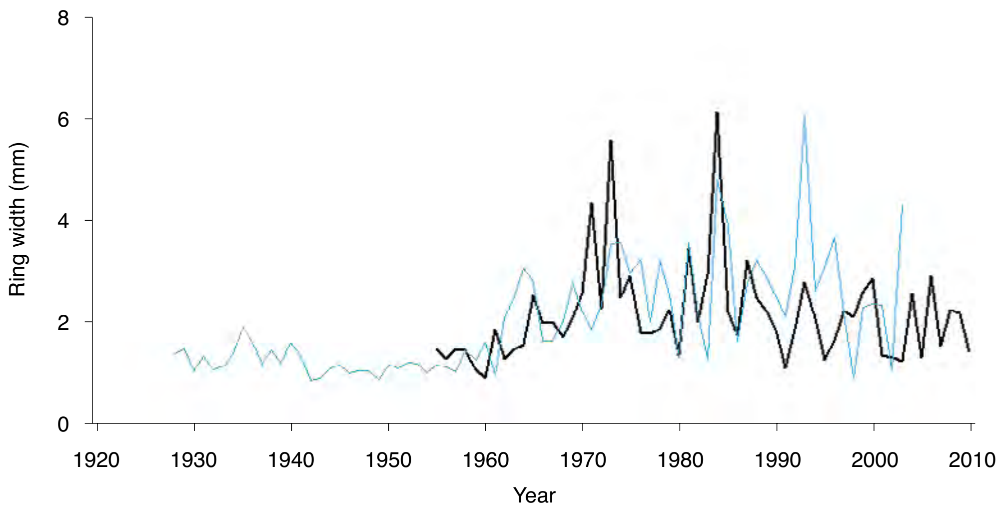


**Figure 10.** Ring-width measurements from two *Podocarpus crassigemmis* trees, showing the potential to match, or cross-date, such measurements among trees

## Discussion and future research

Dendrochronological investigations in the montane forests of Simbu province revealed six tree species with anatomically distinct tree rings. Annual growth rates were reconstructed and C sequestration was estimated for two species: *Nothofagus grandis* and *Podocarpus crassigemmis.*

*Nothofagus grandis* yielded the samples most useful for dendrochronological analysis. The potential of *N. grandis* was also investigated by Ash (1988) in a study of the forests on Mt Giluwe (PNG). Ash confirmed that tree-ring formation was approximately annual using radiocarbon dating. Our study showed that the *N. grandis* at KGWan produced annual growth that was relatively consistent around the stem,

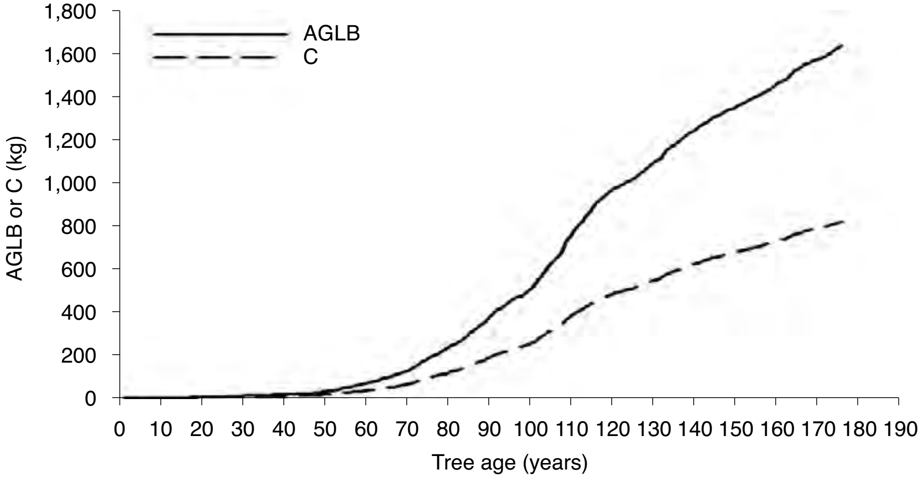


**Figure 11.** Estimated annual carbon (C) sequestration and above-ground live biomass (AGLB) of the oldest *Nothofagus grandis* individual

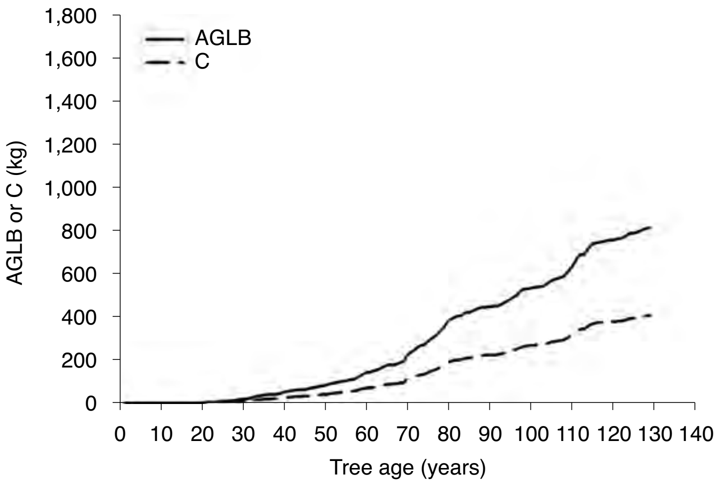


**Figure 12.** Estimated annual carbon (C) sequestration and above-ground live biomass (AGLB) of the oldest *Podocarpus crassigemmis* individual.

as demonstrated by cross-dating of samples within each tree. We also found evidence of synchronous growth among trees (demonstrated by cross-dating among trees), suggesting that growth was influenced by a common factor (e.g. climate). Ash (1988) suggested that ring formation was due to 10–20 rainless days in the June–September period and cold air drainage. Rainfall records from the highland weather station at Goroka, approximately 50 km away from our study site, indicated rainfall seasonality (Figure 13). Preliminary dendroclimatological analyses undertaken for this study also suggested that variation in annual growth in *N. grandis* may be correlated with rainfall, particularly at the beginning of the wet season (unpublished data). However, discontinuities in the instrumental record of climate for PNG pose difficulties in determining the climatic drivers of annual growth, as well as long-term climatic reconstructions from tree rings. Efforts are underway to synthesise the current rainfall dataset (D. Cobon, unpublished data).

*Nothofagus* forests are a valuable resource for timber production and C sequestration. *Nothofagus* wood density is above average, compared with other PNG tree species, and trees have a life expectancy of ~200 years. Estimated annual C sequestration presented for the oldest *N. grandis* tree suggests greater annual growth when the tree is younger and slowing when the tree is older (i.e. ~120 years), possibly with canopy accession. An increased sampling effort focused on *N. grandis* at KGWan, as well as other *Nothofagus* species elsewhere in PNG, is likely to yield important results, clarifying *Nothofagus* forest-stand dynamics such as recruitment patterns, longevity and growth rates. A sampling program at multiple scales may allow isolation of the influence of climate. Because of its position in the Western Pacific Warm Pool, reconstructions of climate variability in PNG could therefore greatly assist in understanding the historical variability of ENSO.

The tree rings of *Podocarpus crassigemmis,* although clear, were prone to wedging, a common feature in the family Podocarpaceae (Dunwiddie 1979; Buckley et al. 1995). Wedging occurs when tree rings are compressed around a section of the tree bole, commonly forming in response to injury or with buttressing. Missing rings and underestimation of age are the most likely outcomes of ring wedging for dendrochronological study. Tree rings were cross-dated within individual trees, increasing our confidence in the estimates of tree age. Annual increase in diameter was also reconstructed. For the oldest *P. crassigemmis,* annual increase in diameter was reconstructed, revealing that the tree had experienced two releases

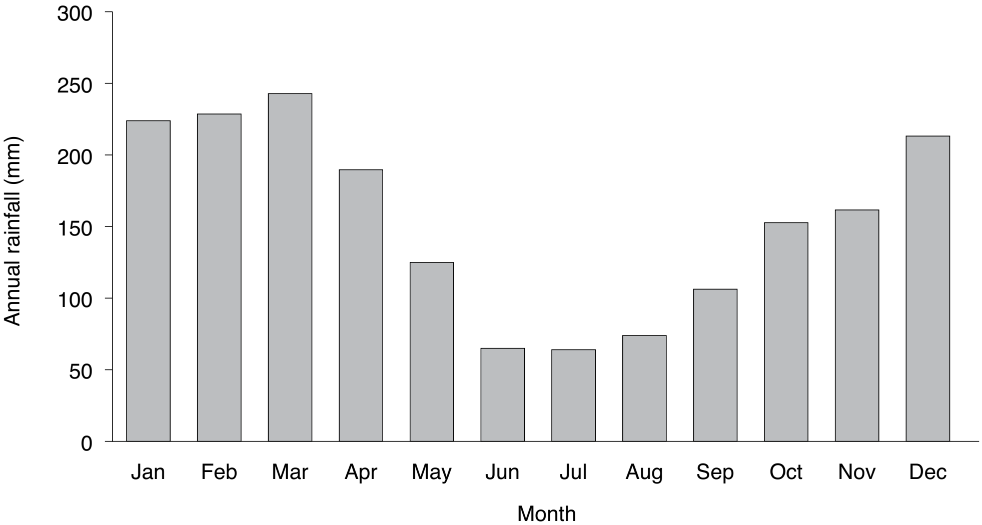


**Figure 13.** Mean monthly rainfall at Goroka (Eastern Highlands, Papua New Guinea); retrieved from PNG National Weather Service, the colonial PNG data archive (Bureau of Meteorology) and the National Agricultural Research Institute at Aiyura for ACIAR by D. Cobon

with a period of ~35 years of suppressed growth in between, and slower growth to the present, indicating that it took two growth spurts to reach the canopy. Overall, C storage was less for *P. crassigemmis* than for *N. grandis*, because trees were typically smaller in height and diameter and wood was less dense.

Cross-dating the growth of multiple individuals to determine a stand-level growth signal for *P. crassigemmis* was problematic because of ring wedging. Nevertheless, the growth of individual trees located in particularly exposed positions on the forest edge appeared to be correlated with rainfall and local disturbance (i.e. growth release post fire (Figure 14). Written records of disturbance at the local scale, such as fire, are scarce. However, there is an opportunity to collect this information from communities where the oral history tradition is strong. Such information may prove to be invaluable in determining the key drivers of historical forest-stand dynamics.

This study has highlighted the potential for dendrochronological studies of forest dynamics in PNG. *Nothofagus grandis* had tree rings that were anatomically distinct and could be cross-dated among multiple trees. *Podocarpus crassigemmis* also had anatomically distinct tree rings, and shows potential for reconstruction of disturbance history due to its forest-edge niche, although problems with ring wedging remain. Furthermore, this study gives details of at least three other species in the mixed species evergreen forest with visible tree rings. Finally, there are many other genera with dendrochronological potential in PNG that have yet to be thoroughly investigated (e.g. *Agathis*, *Vitex*, *Phyllocladus* and *Toona*), each an opportunity for future research.

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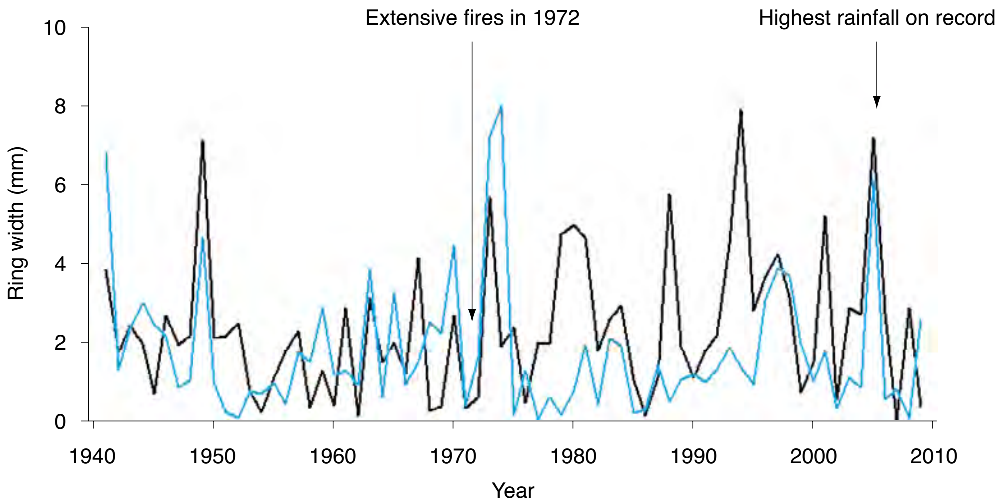


**Figure 14.** Two series of ring-width measurements (in blue and black, respectively) from a single *Podocarpus crassigemmis* tree at the forest–grassland interface; disturbance events are highlighted.

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# Modelling carbon dioxide emissions from selective harvesting in Papua New Guinea

**Julian C. Fox[1*] and Rodney J. Keenan[1,2]**

*Abstract*

In this paper we develop methodology for estimating carbon dioxide ($CO_2$) emissions associated with selective harvesting in Papua New Guinea (PNG). Emissions are estimated based on an assumption of average timber volume extracted per hectare of selective harvesting; this assumption was used in the absence of historical spatial information on land cover and land-cover change for PNG. For each year from 1960 to 2008, the dynamics of forest carbon pools affected by selective harvesting in PNG were estimated.

Estimated emissions from selective harvesting fluctuated between 46 and 61 million tonnes of $CO_2$ ($MtCO_2$) emitted for the period 1996–2008. The methodology was applied to several land-use scenarios (high, medium and low levels of selective harvesting) for the period 2009–20. Estimated emissions for a scenario of high selective-harvesting activity fell from 65 to 52 $MtCO_2$ in this period. For a scenario of low selective-harvesting activity, emissions fell from 65 to 34 $MtCO_2$. The developed methodology and interim estimates of the $CO_2$ emissions associated with selective harvesting facilitate an economic evaluation of the opportunity cost per tonne of $CO_2$ emissions avoided. The methodology also provides an interim forest carbon accounting system as PNG explores systems to monitor, report and verify greenhouse gas emissions from land use, land-use change and forestry.

## Introduction

Papua New Guinea (PNG), along with other rainforest nations, has become the focus of the climate change mitigation initiative REDD+ (reducing emissions from deforestation and forest degradation and enhancement of forest carbon stock). Hence, there has been interest both from within PNG and among the international scientific community to develop methodology to support the REDD mechanism. The forest assessment work undertaken as part of Australian Centre for International Agricultural Research (ACIAR) project FST/2004/061 provided an opportunity for ground-based estimation of forest carbon (C) from permanent sample plots (PSPs) (Fox et al. 2010), and estimates of changes in C due to sequestration in regrowth and selective harvesting (Fox et al. 2011a).

PNG has about 33 million ha (Mha) of tropical forests, which have been subject to a high rate of conversion due to selective harvesting and agriculture (Shearman et al. 2009; Filer et al. 2009; Shearman et al. 2010). An important technical challenge is to understand the change in forest C stocks due to harvesting (Kauffman et al. 2009) and the regrowth C dynamics after harvesting (Olander et al. 2008). In Fox et al. (2011a) the impact of selective harvesting and regrowth C sequestration was estimated using the PSPs. To achieve this, a hierarchical Bayesian model (HBM) was used to derive parameters that can be used to estimate the C and carbon dioxide ($CO_2$) balance of selective harvesting and forest regeneration, which are important inputs for climate change mitigation initiatives such as REDD+.

Selective harvesting changes the C balance of forest ecosystems—some C pools decompose, returning $CO_2$ to the atmosphere (harvesting residues); some

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sequester, removing $CO_2$ from the atmosphere (regrowing forest); some store $CO_2$ (wood products); while others release $CO_2$ through combustion (burning sawmill residue). Most importantly, selective harvesting results in the displacement of living forest biomass to non-living biomass, a component of which is taken off site as wood products, with the remaining displacement termed collateral damage and becoming decomposing residue on the forest floor (Blanc et al. 2009). In Fox et al. (2011a) we estimated the change in C stock due to selective harvesting as 75 ± 25 tC/ha—a 55% reduction in above-ground live biomass (AGLB). Similar reductions have been observed elsewhere, with surprising consistency; Lasco et al. (2006), Tangki and Chappell (2008), Feldpausch et al. (2006), and Gerwing (2002) all observed 50% reductions in AGLB in the Philippines, Borneo, southern Amazon and Brazilian Amazon respectively. In Fox et al. (2011a), observed C sequestration in regrowth was estimated to be 1.12 ± 3.41 tC/ha/year. These estimates can provide a quantitative basis for estimating estate-wide emissions from forests, which is undertaken in this paper. Forest C accounting systems need to be developed for PNG as it explores systems to measure, report and verify (MRV) greenhouse gas emissions from land use, land-use change and forestry (see Fox et al. 2011b).

In this paper we undertake an analysis of the C dynamics of PNG forests based on the estimates of Fox et al. (2010, 2011a). In the absence of explicit MRV guidelines for the REDD+ mechanism (although methodological guidance is emerging from the Copenhagen and Cancun texts; see Fox et al. 2011b), this methodology for estimating $CO_2$ emissions associated with selective harvesting is based on available literature as referenced, such as published C bookkeeping methods (e.g. Ramankutty et al. 2007; Blanc et al. 2009) and elements of the Voluntary Carbon Standard (VCS 2008a, b, c) and IPCC guidelines (IPCC 2003, 2006).

Aside from selective harvesting, subsistence agricultural activities have also been identified as a contributor to emissions from land use, land-use change and forestry in Papua New Guinea. Here, a young boy looks on as an area of community forest in Madang province is cleared and burnt in preparation for planting (Photo: Julian Fox).

## Methodology

For each year over the period 1960–2008 the C pools affected by selective harvesting in PNG were estimated. Most of the affected C pools were above ground; however, there will be an enhanced pool of below-ground residue from dead biomass in roots and stumps. Other below-ground C pools such as soil C were not considered because they were unlikely to change due to selective harvesting in the considered time frames (Hughes et al. 1999; IPCC 2006; Yashiro et al. 2008).

For ease of interpretation, lookup tables are provided below for all variables and all parameters used in the selective-harvesting emissions model for PNG. Table 1 describes model variables, each symbol used and their occurrence. Table 2 describes model parameters as well as their value and the authority on each value.

Figure 1 provides a simplified diagrammatic flow chart of emissions calculations.

### Estimating selective-harvesting area

The annual (year $i$) area affected by selective harvesting ($SHA_i$) was estimated from the sum (total volume; $TV_i$) of roundwood log export volume ($EV_i$) and the volume of locally processed timber ($LPV_i$), and an assumption of average removals per hectare (equation (1); 15 m³/ha; Keenan et al. 2005, 2009):

$$
\begin{aligned}
TV_i &= EV_i + LPV_i \\
SHA_i &= (EV_i + LPV_i)/15
\end{aligned}
\qquad (1)
$$

where: $EV_i$, $LPV_i$ and $TV_i$ are log export, locally processed and total extracted volume, respectively, from native forests in PNG for year $i$.

**Table 1.** Parameters used in the Papua New Guinea selective-harvesting emissions model, and their value and authority

| Parameter description | Parameter value | Authority | Equation |
|---|---|---|---|
| Average timber volume removals (m³/ha) | 15 | Keenan et al. (2005) | 1 |
| Carbon fraction of dry timber | 0.5 | Houghton et al. (2001) | 3 |
| Change in AGLB due to harvesting (tC/ha) | 70 | Fox et al. (2011a) | 3,4 |
| Selectively harvested forest AGLB (tC/ha) | 75 | Fox et al. (2011a) | 3,8 |
| Average commercial wood density (kg/m³) | 0.58 | Authors' analysis | 3,16 |
| Ratio harvested area to deforested area | 0.15 | Pulkki (1997) | 5 |
| Primary forest AGLB (tC/ha) | 137 | Fox et al. (2011a) | 5 |
| Failed regrowth (tC/ha) | 50 | Authors' analysis | 7 |
| Failed regrowth rate parameter | –16 | Authors' analysis | 7 |
| Below-ground to above-ground biomass | 0.37 | IPCC (2006) | 8 |
| Ratio of large wood to fine debris | 0.43 | Authors' analysis | 11 |
| Largewood emissions decay rate | –0.1 | Keller et al. (2004) | 12 |
| Smallwood emissions decay rate | –0.2 | Keller et al. (2004) | 12 |
| Successful regeneration (%) | 0.75 | Yosi et al. (2011) | 13 |
| Recovery period carbon acquisition (tC/ha) | 75 | Fox et al. (2011a) | 15 |
| Successful regrowth rate parameter | –16 | Authors' analysis | 15 |
| Carbon fraction wood product multiplier | 0.98 | IPCC (2006) | 16 |
| Average tropical sawn recovery (%) | 0.33 | Blanc et al. (2009) | 16 |
| Felling Fuel Consumption multiplier | 0.0015 | Klvac and Skoupy (2009) | 20 |
| Loading Fuel Consumption multiplier | 0.00105 | Klvac and Skoupy (2009) | 20 |
| Average volume carried on each truck (m³) | 10 | Kinjo et al. (2005) | 22 |
| Average haulage distance (km) | 50 | Authors' analysis | 22 |
| Fuel efficiency (km/kL) | 3,000 | Kinjo et al. (2005) | 22 |
| Petrol emission factor | 2.3 | USEPA (2009) | 23 |
| Diesel emission factor | 2.7 | USEPA (2009) | 24 |

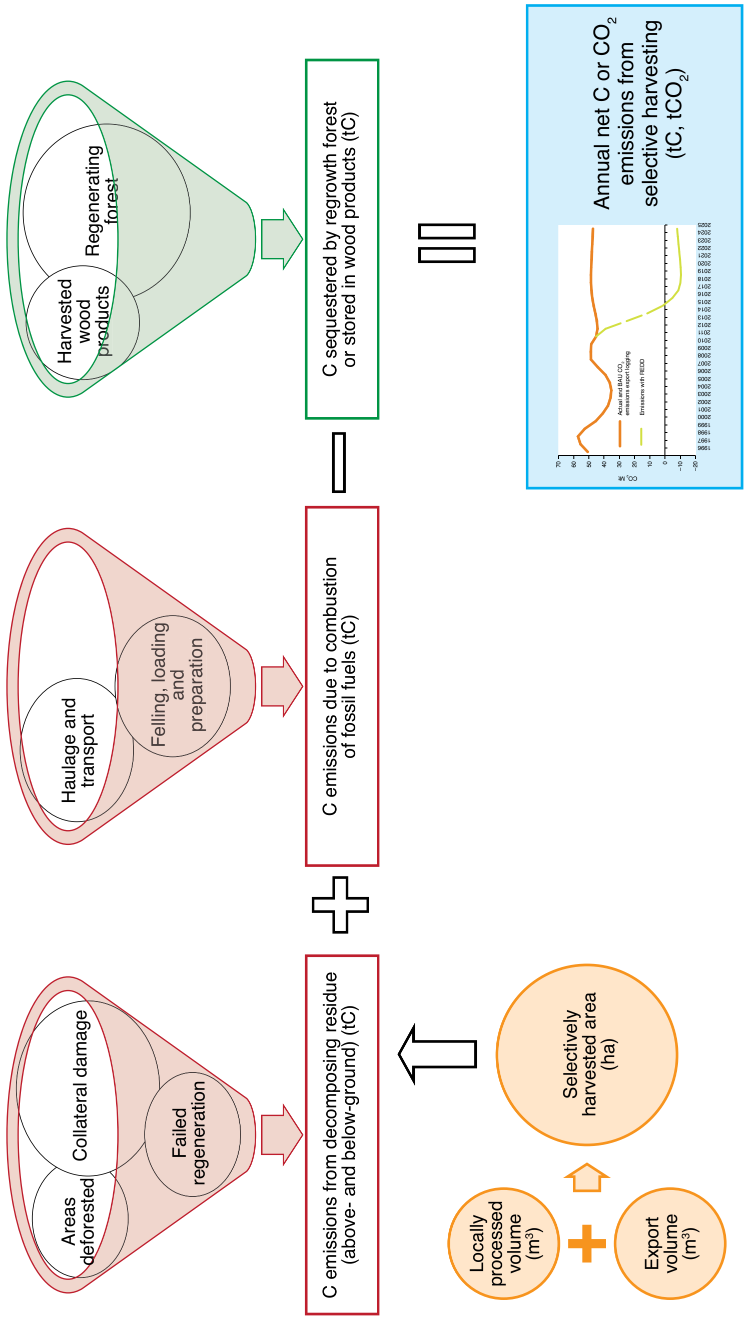


**Figure 1.** Diagrammatic flow chart of selective-harvesting emissions model for Papua New Guinea

**Table 2.** Variables used in the Papua New Guinea selective-harvesting emissions model, and their symbols and occurrence

| Variable description | Symbol | Equation |
|---|---|---|
| Log export volume ($m^3$) | $EV_i$ | 1 |
| Locally processed volume ($m^3$) | $LPV_i$ | 1 |
| Total volume extracted ($m^3$) | $TV_i$ | 1 |
| Selectively harvested area (ha) | $SHA_i$ | 1,4 |
| C in decomposing residue (tC) | $DR_i$ | 2 |
| C sequestered in regrowth (tC) | $CR_i$ | 2 |
| Stock change of C in harvested wood products (tC) | $NCWP_i$ | 2, 18 |
| C combusted during fuel consumption (tC) | $EFC_i$ | 2 |
| C in collateral damage (tC) | $CD_i$ | 4 |
| Area deforested (ha) | $AD_i$ | 5 |
| Area failed regeneration (ha) | $AFR_i$ | 6 |
| C in failed regrowth (tC) | $FR_n$ | 7 |
| C in below-ground residue (tC) | $BR_i$ | 8 |
| C in largewood decomposing residue (tC) | $LW_i$ | 11 |
| Area of successful regeneration (ha) | $ASR_i$ | 13 |
| C in successful regeneration (tC) | $SR_n$ | 15 |
| C in wood products (tC) | $CWP_i$ | 16 |
| Emissions from wood products (tC) | $EWP_i$ | 17 |
| Emissions from fuel consumption (tC) | $EFC_i$ | 19 |
| Fuel consumption felling (kL) | $FEL_i$ | 20 |
| Fuel consumption loading (kL) | $LD_i$ | 21 |
| Fuel consumption preparation (kL) | $PREP_i$ | 21 |
| Fuel consumption transport (kL) | $TR_i$ | 22 |

## Estimating emissions from selectively harvested area

$CO_2$ emissions associated with the selective-harvesting area ($CSH_i$) in year $i$ were estimated based on emissions from an accumulating pool of decomposing residue ($DR_i$), observed C sequestered in regrowth ($CR_i$), net stock change of C stored in harvested wood products ($NCWP_i$), C combusted during fuel consumption ($EFC_i$) and the stoichiometric conversion ratio from C to $CO_2$ equivalent of 44/12 (equation (2); Blanc et al. 2009; VCS 2008b, c):

$$CSH_i = [DR_i - CR_i - NCWP_i + EFC_i] \times [44/12] \quad (2)$$

## Observed reductions in above-ground live biomass due to selective harvesting

Fox et al. (2011a) found that, on average, selectively harvested forest had 75 tC/ha less AGLB than primary forest immediately after harvesting (137 tC/ha compared with 62 tC/ha). Therefore, we can assume that the C fraction of AGLB displaced in selective harvesting (*RSH*) is approximately 75 tC/ha.

A component of this 75 tC/ha will be moved off site as wood products. A larger component will become dead biomass including tree crowns, non-merchantable materials and trees killed. Collectively, we can refer to this pool as 'collateral damage', which will become decomposing residue. We can estimate this large pool by subtracting the C fraction of the assumed timber volume removals of 15 $m^3$/ha. The carbon fraction can be estimated from the average wood density for commercial timber species in PNG. This was calculated using an average of species' wood density weighted by the annual volume of timber removed from the forest. The weighted average wood density of exported timbers was 0.58 $t/m^3$. Therefore, the contribution to decomposing residue from collateral damage after harvesting can be calculated as (equation (3)):

$$\Delta CD = 75 - [15 \times 0.50 \times 0.58] \quad (3)$$

Collateral damage ($CD$) resulting from selective harvesting is therefore 70 tC/ha, and can be estimated nationally from the selectively harvested areas ($SHA_i$; equation (4)):

$$CD_i = SHA_i \times 70 \quad (4)$$

The decomposing residue pool ($DR_i$) consists of a one-off contribution from displaced living biomass (calculated above), as well as contributions from living biomass displaced from areas deforested ($AD_i$), failed regeneration ($FR_i$), and below-ground residue ($BR_i$).

### Areas deforested

Areas are deforested during selective harvesting due to road construction, log dumps, harvesting camps and other infrastructure. The ratio of total selectively harvested area to deforested area has been estimated to be 15% in tropical operations (Pulkki 1997). The average C fraction of AGLB in primary forest in PNG was estimated in Fox et al. (2011a) to be 137 tC/ha. A component of this will be removed from the forest during selective harvesting as wood products (estimated below), but the majority will remain in the forest as decomposing residue. Therefore, the C fraction of biomass displaced from deforested areas and contributing to decomposing residue can be estimated as (equation (5)):

$$AD_i = [0.15 \times SHA_i \times 137] - [SHA_i \times 15 \times 0.50 \times 0.58] \quad (5)$$

### Failed regeneration

Selectively harvested areas that fail to adequately regenerate (failed regeneration; $FR_i$) will annually contribute to the decomposing residual pool due to tree mortality. Analysis of forest recovery after selective harvesting has indicated that 25% of areas in PNG fail to adequately recover due to poor harvesting practices, subsequent anthropogenic disturbance (shifting cultivation) and fire disturbance (Yosi et al. 2011). This component of selectively harvested forest will accumulate annually, and will contribute

Roads created to access the forest can account for a relatively large proportion of effected area during selective-harvesting operations. Here is a temporary logging road constructed in Western Sepik province (Photo: Joe Pokana).

to the decomposing residual pool due to ongoing tree mortality. An inverse of the average sequestration rate (1.1 tC/ha/year; see section 'Estimating C sequestered in regrowth' below) can be used to characterise mortality and to estimate the C lost to mortality in forests with failed regrowth. The area of failed regeneration in year *i* ($AFR_i$) can be estimated as (equation (6)):

$$AFR_i = SHA_i \times 0.25 \tag{6}$$

The total magnitude of this contribution in year *n* ($FR_n$) can be estimated as the sum of contributions from failed regrowth from previous years as well as the present year (equation (7)):

$$FR_n = \sum_{i=1961}^{n} \left[ [62 - 50(e^{-16/t})] \times AFR_i \right] \tag{7}$$

where: *t* is the time since selective harvesting. See the section 'Estimating C sequestered in regrowth' below for further explanation of equation (7).

## Below-ground residue

Selective harvesting will result in an enhanced pool of below-ground residue in the root material of harvested trees. The component of total below-ground biomass affected can be estimated from the amount of above-ground biomass affected and the application of established ratios (Herold et al. 2008). The IPCC (2006) recommends a ratio for below-ground to above-ground biomass of 0.37 for lowland tropical forests. By applying this ratio to the observed reduction in AGLB due to selective harvesting (*RSH*; 75 tC/ha; Fox et al. 2011a), we can estimate the amount of below-ground residue ($BR_i$; equation (8)):

$$BR_i = SHA_i \times 75 \times 0.37 \tag{8}$$

## Total pool of decomposing residue

The decomposing residue pool in year *n* ($DR_n$) therefore consists of accumulating contributions from living biomass displaced from collateral damage $CD_i$, areas deforested ($AD_i$), failed regeneration ($FR_i$) and below-ground residue ($BR_i$; equation (9)):

$$DR_n = \left[ \sum_{i=1961}^{n} (CD_i + AD_i + FR_i + BR_i) \right] \tag{9}$$

## Decomposition of harvesting residues

The pool of decomposing residue will release $CO_2$ into the atmosphere. When estimating decomposition rates, it is important to separate the fine debris ($FD_i$) pool from the largewood ($LW_i$) pool as the two pools decompose at very different rates. The fine debris pool, which consists of leaves, twigs and small-diameter branches, will decompose rapidly, while large woody biomass will decompose at a much slower rate (Chambers et al. 2004; Keller et al. 2004; Blanc et al. 2009). The ratio of largewood to fine debris was estimated using PSP data for primary forests collected by the PNG Forest Research Institute (PNGFRI). The ratio ($R_{LWFD}$) was determined by first summing stem volumes ($SV_i$) (adjusted for wood density for species *T* ($WD_T$) and the carbon fraction of biomass, 0.5) for all trees (*i*) on the 1-ha PSPs. This was then divided by the summed carbon fraction of AGLB (equation (10); Blanc et al. 2009):

$$R_{LWFD} = \frac{\sum_{i=1}^{n} SV_i \times WD_T \times 0.5}{\sum_{i=1}^{n} AGB_i} \tag{10}$$

This ratio was estimated for 12 primary forest plots that were averaged, resulting in a ratio of 0.43. The proportion of decomposing residue attributable to the largewood ($LW_i$) pool is then (equation (11)):

$$LW_i = DR_i \times 0.43 \tag{11}$$

The decomposition rates of the largewood and fine debris pools were based on reported values from the literature, using an exponential decay formula (equation (12); Chambers et al. 2000; Keller et al. 2004; Blanc et al. 2009):

$$DR_i = DR_{i-1} e^{-kt} \tag{12}$$

Therefore, the decomposing residue ($DR_i$) pool in year *i* is $DR_{i-1}$ (decomposing residue in year *i–1*) multiplied by the exponent of the decay rate (*k*) multiplied by the time (*t*) since deposition.

Fine debris pools will decompose rapidly with a decay rate of 0.2 ($k_{FD}$ = 0.2), which results in a half-life of about 3 years (Keller et al. 2004). Largewood pools will decompose more slowly, with a decay rate of 0.1 ($k_{FD}$ = 0.1), which results in a half-life of about 8 years.

### Estimating C sequestered in regrowth

Yosi et al. (2011) found that 75% of selectively harvested forest successfully regenerates. Therefore, the area of successful regeneration in year $i$ ($ASR_i$) can be estimated as (equation (13)):

$$ASR_i = SHA_i \times 0.75 \tag{13}$$

Carbon sequestered in regrowth was estimated from the accumulative area of successful regeneration ($ASR_i$) and observed average C sequestration for selectively harvested forest (1.1 tC/ha/year; Fox et al. 2011a). To replicate the sigmoidal tendency of forest recovery, a simple model was adopted from the forest recovery function of Australia's National Carbon Accounting System. The function is appealing because the parameters are readily interpretable, with the first parameter representing the upper asymptote (primary forest C; 137 tC/ha) and the second parameter representing the shape of the curve to this asymptote (Brack et al. 2006), which was modified here for the addition of AGLB after selective harvesting (62 tC/ha) and the acquisition of 75 tC/ha over the recovery period (equation (14)):

$$C_t = 62 + 75(e^{-k/t}) \tag{14}$$

where: $C_t$ is the above-ground C $t$ years after selective harvesting and $k$ is the rate parameter. By assuming a recovery rate of 1.1 tC/ha/year between 0 and 20 years after harvesting (measurement periods for PSPs; Fox et al. 2011a) and a recovery period of 100 years, $k$ was estimated to be 16. This resulted in an average annual sequestration rate of 1.1 over the first 20 years of recovery, which matches empirical data (Figure 2; Fox et al. 2011a).

Following this model, regrowth forest is still sequestering C after 100 years, albeit at a reduced rate (Figure 2). Therefore, the C stock in successfully regenerating forest ($SR_n$) in year $n$ can be estimated from the accumulating area of successful regeneration multiplied by the predicted recovery function (equation (15)):

$$SR_n = \sum_{i=1961}^{n} \left[ [62 + 75(e^{-16/t})] \times ASR_i \right] \tag{15}$$

Annual C sequestration in regrowth ($CR_i$) can be estimated as the annual change in $SR_n$.

### Estimating C stored in wood products

Carbon stored in harvested wood products $CWP_i$ was calculated from annual roundwood export and locally processed timber volumes, average recovery (33% recovery in tropical sawn timbers; Blanc et al. 2009), average wood density for utilised commercial timber species (*WD*; 0.58), the C fraction of dry timber (default is 0.5), the fraction of solid dry wood that decays annually, and the average life span of tropical timber in China (industry advises that this is approximately 5 years). This approach is known as the stock change approach (Dias et al. 2009). Annual decay rates for solid tropical timbers have

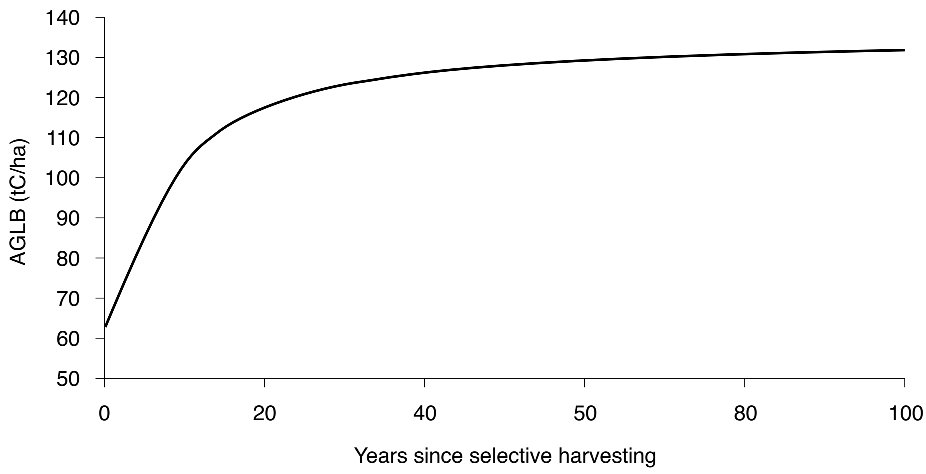


**Figure 2.** Above-ground live biomass dynamics (AGLB) after selective harvesting

been estimated to be 0.02 (Winjum et al. 1998; IPCC 2006); therefore, a multiplier of 0.98 on the C fraction of wood products is appropriate to estimate C stored in wood products. The addition of C in year *i* can be calculated as (equation (16)):

$$CWP_i = TV_i \times 0.33 \times 0.58 \times 0.5 \times 0.98 \tag{16}$$

where: $TV_i$ is the total extracted volume from native forests in PNG for year *i*. The C fraction of roundwood sawmill waste (66%) was assumed to be burned, as is common practice in local processing and in export countries such as China, and was immediately decomposed with the C fraction emitted.

Stock change can be calculated as the annual addition of C to the wood product pool ($CWP_i$) less the emissions from annual decay and product destruction after 5 years. The C emissions associated with harvested products in year *i* ($EWP_i$) from decay and product destruction after 5 years can be calculated as (equation (17)):

$$EWP_i = \left[\sum_{i-4}^{i} CWP_i \times 0.02^t\right] + CWP_{i-5} \tag{17}$$

where: $t$ is the number of years since $CWP_i$ entered the pool of harvested wood products. The calculation is based on the number of years over which C accumulates in wood products (assumed to be 5 years). The emitted quantity ($EWP_i$) needs to be subtracted from the C added ($CWP_i$) to estimate the net stock change in year *i* ($NCWP_i$; equation (18)):

$$NCWP_i = CWP_i - EWP_i \tag{18}$$

The net amount of C stored in wood products can then be added as a C sink.

### Estimating $CO_2$ emissions from fuel consumption

Emissions from fuel consumption in year *i* ($EFC_i$) associated with selective harvesting is the summation of consumption from felling ($FEL_i$), preparation ($PREP_i$), loading ($LD_i$) and transport ($TR_i$), and the emission factor for each fuel type ($E_{FEL}$, $E_{PREP}$, $E_{LD}$, $E_{TR}$; equation (19)):

$$\begin{aligned} EFC_i = {} & (FEL_i \times E_{FEL}) + (PREP_i \times E_{PREP}) \\ & + (LD_i \times E_{LD}) + (TR_i \times E_{TR}) \end{aligned} \tag{19}$$

Fuel consumptions (in kilolitres) due to felling and loading are a function of the total extracted volume (equation (20); Klvac et al. 2003; Klvac and Skoupy 2009):

$$\begin{aligned} FEL_i &= TV_i \times 0.0015 \\ LD_i &= TV_i \times 0.00105 \end{aligned} \tag{20}$$

where: $TV_i$ is the total extracted volume from native forests in PNG for year *i*. Fuel consumption due to preparation is assumed to be equivalent to consumption for felling (equation (21)):

$$PREP_i = FEL_i \tag{21}$$

Fuel consumption associated with transport is a function of the extracted volume, the average volume carried on each truck ($VT_i$, 10 $m^3$; Kinjo et al. 2005), the average haulage distance ($HD_i$, estimated to be 50 km for PNG) and fuel efficiency (3,000 km/kL; Kinjo et al. 2005; equation (22)):

$$TR_i = (TV_i/VT) \times (HD_i/FE) \tag{22}$$

The emission factor for petrol (felling and preparation) is 2.3 $tCO_2$/kL (equation (23)):

$$E_{FEL}, E_{PREP} = 2.3 \tag{23}$$

The emission factor for diesel (loading and transport) is 2.7 $tCO_2$/kL (equation (24)):

$$E_{TR}, E_{LD} = 2.7 \tag{24}$$

Both emission factors are from the United States Environment Protection Agency <http://www.epa.gov/oms/climate/420f05001.htm>, accessed November 2009.

## Results

### Results 1961–2008

National log export data (excluding plantation logs) and locally processed volumes are available for PNG from 1961 to 2008 (Hunt 2010; Bank of Papua New Guinea, various; SGS PNG Ltd, various). The trend in log export data is depicted in Figure 3.

Using the methodology described above, the C and $CO_2$ emissions contributions from various sources can be estimated and examined. Figure 4 depicts annual additions to the decomposing residue pool. Collateral damage is the largest addition to decomposing residue, followed by C losses in below-ground biomass, area deforested and failed regrowth.

Figure 5 depicts component emissions and indicates the relative contributions of decomposing residue, fuel consumption, regrowth sequestration and C storage in harvested wood products. Note that negative emission is C sequestration. It can be

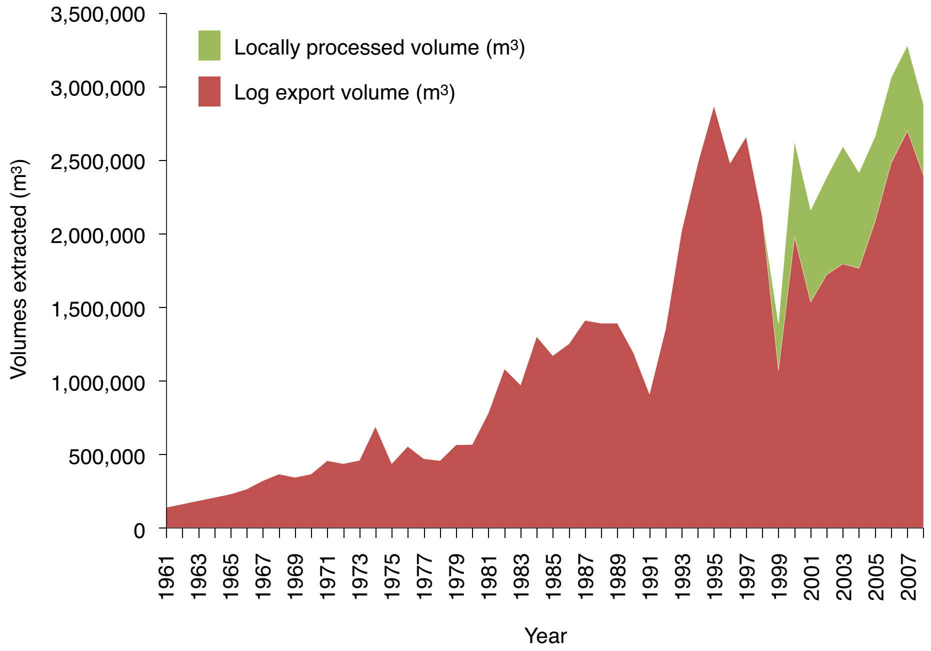


**Figure 3.** Timber volumes extracted from Papua New Guinea's native forests

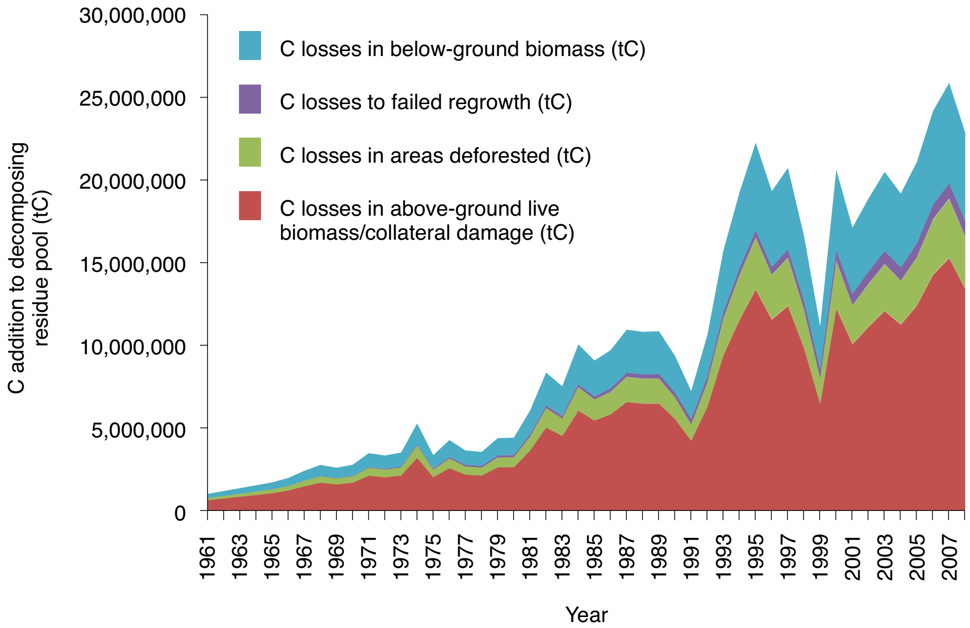


**Figure 4.** Annual additions to decomposing residue pool

observed that emissions from decomposing residue are the single most important source, while regrowth sequestration is increasing as this pool accumulates. C emissions due to fuel consumption and C storage in wood products are relatively insignificant.

Based on the methodology described above, the total $CO_2$ emissions associated with selective harvesting can be estimated, as depicted in Figure 6.

### Results 1996–2020

The period 1996–2008 has been identified as a baseline period for more detailed study. Log extraction data is available for PNG for this period (SGS various years). This has been projected for 2009–20 under three scenarios—low, medium and high projected increase in selective harvesting (Hunt 2011).

We can estimate the $CO_2$ emissions associated with these scenarios, as in Figure 7.

It can be noted from Figure 7 that emissions tend to fall away after peaking in 2014. This is because extraction rates are lower than the peak of 2006, which results in a lagged peak in emissions in 2008.

## Discussion

We developed methodology for estimating estate-wide $CO_2$ emissions associated with selective harvesting in PNG. The estimated change in C stock due to selective harvesting was used for preliminary national estimates of harvesting-related emissions. Coote and Fox (2011) undertake a sensitivity analysis of the model to determine the sensitivity of $CO_2$-emission estimates to different model inputs. The estimation of selective-harvesting area using the above methodology is an interim approach—it is envisaged that future approaches will use remote sensing data sources for a historical reconstruction and to more explicitly and accurately identify affected areas (e.g. Asner et al. 2002, 2004). The above method is reliant on the generality of 15 $m^3$/ha as the average volume removed in selective harvesting. Concession-level analysis of net available area, net volume and volumes of roundwood export and locally processed timber confirm that 15 $m^3$/ha is suitable for this purpose. The application of this figure to harvest volumes during 1961–2008

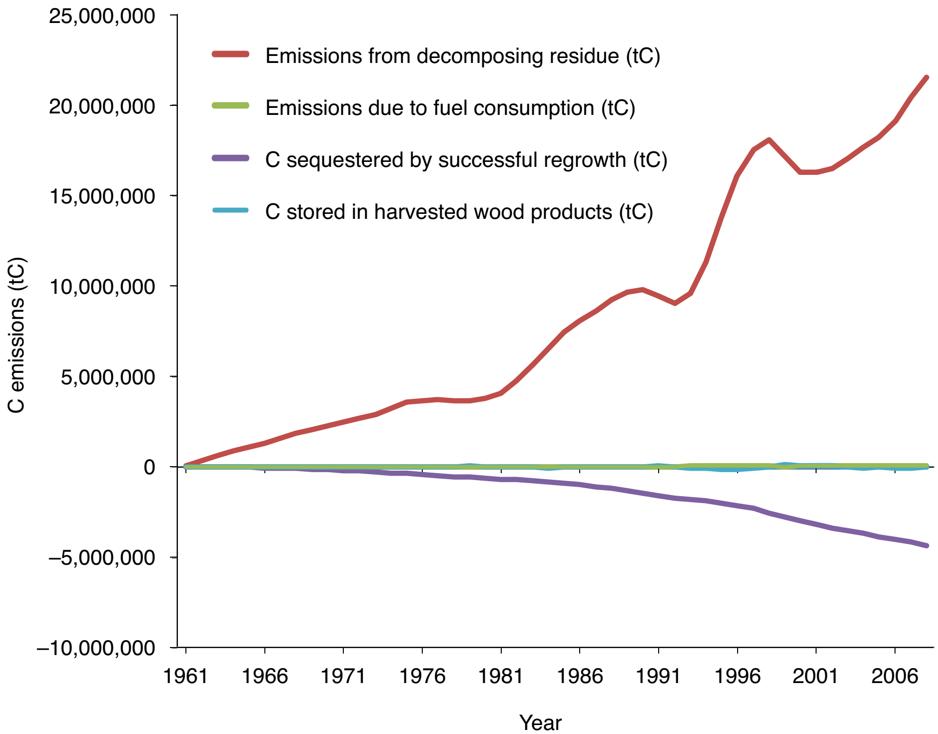


**Figure 5.** Component annual C emissions associated with selective harvesting

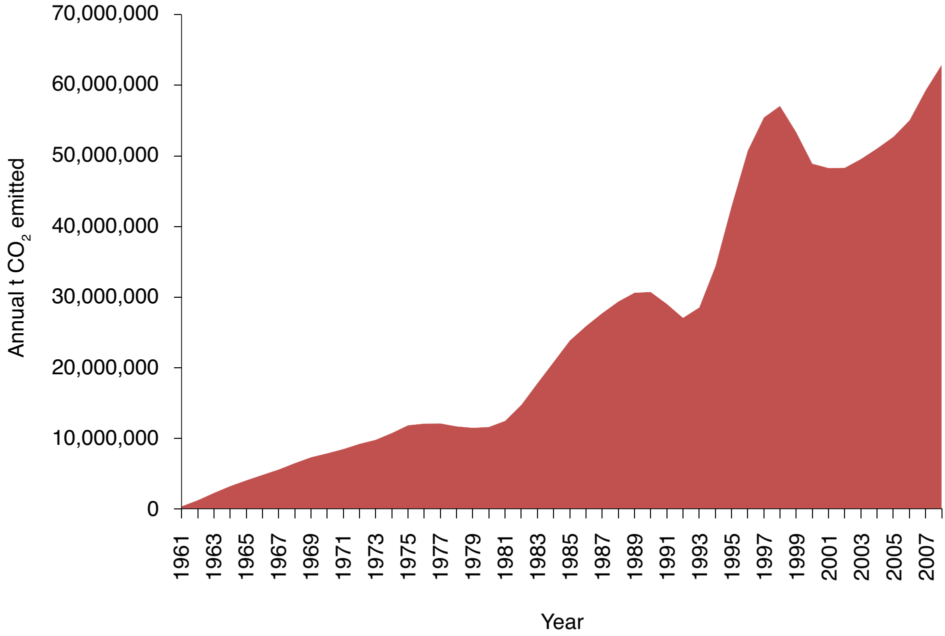


**Figure 6.** $CO_2$ emissions associated with selective harvesting

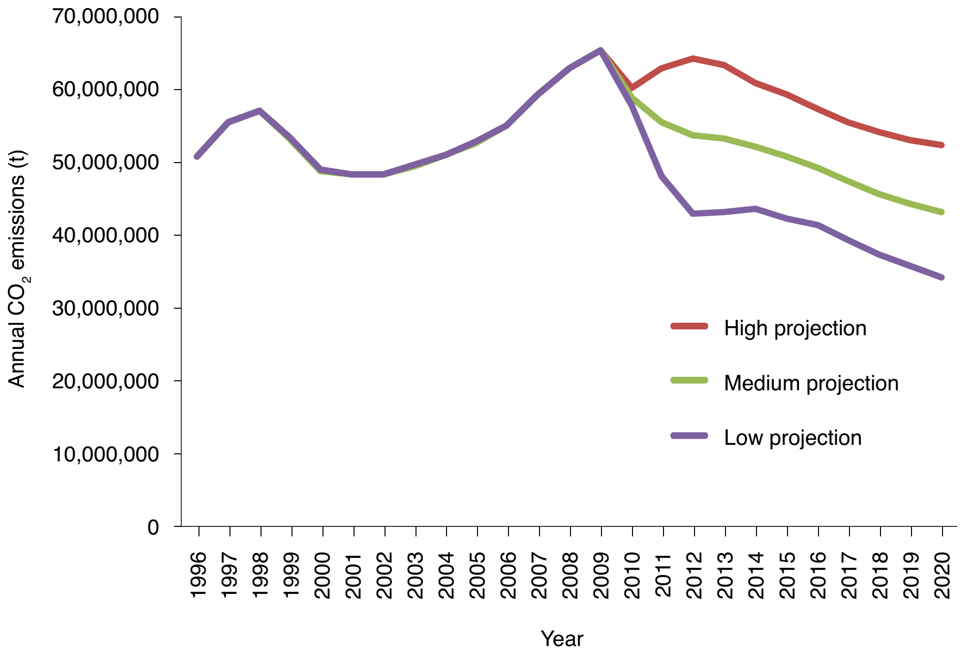


**Figure 7.** $CO_2$ emissions under three scenarios, 1996–2020

resulted in a total selectively harvested forest area of 3.7 Mha. This is similar to the Papua New Guinea Forest Authority (PNGFA) estimate of selectively harvested forest (up to 2002) of 3.4 Mha. However, more analysis is recommended to test the generality of this assumption.

A simplifying assumption is applied in calculating fuel consumption associated with selective harvesting with an average haulage distance of 50 km. The actual haulage distance could be estimated on a concession basis using geographic information systems (GISs) and a network analysis of haulage routes (Healey et al. 2009). However, this spatial information is not currently available. If it was, it could be integrated with concession-level extracted volumes to more accurately estimate the emissions associated with haulage. Fuel consumption associated with the shipping of roundwood exports to overseas markets (principally China) was not included in the current analysis. However, this source of $CO_2$ may be significant and should be considered for inclusion in future work.

As defensible land-cover classifications and biomass maps become available for PNG, there is an opportunity to create an integrated forest-based $CO_2$ assessment system. Such a system would require that spatial information be integrated with data on harvested coupes, haulage, timber recovery and harvesting residue from PNGFA and SGS, and information on forest types, growth rates and stand age from PNGFRI. Data could be integrated into a GIS and a more accurate $CO_2$ profile established for forestry activities. This would include emissions associated with transport, machinery and decomposing residue, sequestration in regrowth, and storage in wood products in a spatially explicit framework.


Emissions from machinery and transport were found to be only a small component of the net emissions from selective harvesting in Papua New Guinea. A jinker truck was used for log haulage by Rimbunan Hijau (Photo: Jim Grigoriou).

Log landings such as this in Madang province are deforested during selective harvesting, with total removal of above-ground biomass (Photo: Julian Fox).

Such an approach would identify the major sources of forestry-related emissions that can be targeted in adjusting to a future low-C economy. Other opportunities can also be explored and quantified; for example, a reduction in the overall rate of harvesting, reduced-impact harvesting and other changes to harvesting and transport practices, silvicultural treatment to improve regrowth sequestration rates, restoration of degraded areas and potential plantation establishment on suitable cleared land near roads and infrastructure. Because the work would be spatially explicit and based on actual PNGFA management plans, baseline emissions from current practices could be explicitly compared with emissions under different adaptation scenarios. An integrated assessment model of forest-based $CO_2$ dynamics could form part of PNG's measurement, reporting and verification (MRV) system, which would be useful for communities and provincial and national governments for analysis and assessment, and could facilitate participation in a REDD+ mechanism.

Emissions are estimated based on an assumption of average timber volume extracted per hectare of selective harvesting; this assumption was used in the absence of up-to-date spatial information on land cover and land-cover change for PNG. It is recommended that this methodology and the resulting estimates be revised as REDD+ guidelines become available and spatial information for PNG improves.

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# Methodologies for REDD reporting and decision-making

**Colin Hunt[1*]**

*Abstract*

The chapter sets out methodologies for assessment of the emissions abated by REDD (reducing emissions from deforestation and forest degradation) proposals and the opportunity costs of doing so. It does this in the context of the prevailing funds-based approaches to REDD in the absence of a global market for carbon. Developing countries need to carefully estimate the opportunity costs of REDD, not only for reporting purposes, but also to ensure that the country and stakeholders are not economically disadvantaged by REDD proposals. Donors, on the other hand, as well as needing to be satisfied about the veracity of abatement of $CO_2$ emissions under REDD, need to know the relative costs per tonne of abatement of REDD proposals. Methodologies for deriving the relative costs of REDD projects per tonne of $CO_2$ abated are also detailed. In the case of Papua New Guinea, it is shown that landowners are important beneficiaries of selective harvesting for export. Given the need for improved rural livelihoods and regional development, the Papua New Guinea Government and prospective donors alike will need to be satisfied that REDD proposals that substitute for harvesting carry genuine development benefits. Further research is needed on how to achieve the delivery of these benefits to landowners in the event of a REDD scheme.

## Introduction

### International developments

The modelling of a country's emissions from land-use change, and particularly from deforestation, is important, from both international and national perspectives. About 12% of global carbon (C) emissions are caused by deforestation, mostly in tropical developing countries (Le Quéré et al. 2009; van der Werf et al. 2009), with Asian-Pacific countries as a group being the largest contributor. Actions that effectively reduce deforestation in these countries will be important in supplementing actions that reduce emissions from the burning of fossil fuels.

The Kyoto Protocol, for which the first commitment period expires in 2012, did not require developing countries to reduce their emissions. The Clean Development Mechanism (CDM) allowed for those countries with commitments to invest in projects in developing countries to reduce emissions and claim these credits towards their target commitments. However, CDM projects in the land sector were restricted to afforestation and reforestation, and they were not rewarded for a reduction in C emissions from deforestation. This is despite the fact that reducing deforestation has an immediate impact on emissions—in contrast to the delayed effect of plantation forestry in sequestering C. The substantial practical difficulties in measuring and guaranteeing the C captured by forests explain why there has been an absence of coordinated international action to mitigate emissions from tropical deforestation.

Building on the work of the United Nations Framework Convention on Climate Change (UNFCCC), the Bali action plan of 2007 led to agreed actions at the Copenhagen climate change conference in 2009 to stimulate: 1. policy proposals and positive incentives to reduce emissions from deforestation and forest degradation (REDD), and

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2. the role of conservation, sustainable forest management and the enhancement of forest C stocks in developing countries. While the Copenhagen conference failed to create conditions for a global C market, the Copenhagen Accord nevertheless included substantial financial pledges, through funds-based schemes, in support of REDD. The accord was followed by pledges on emissions reductions by individual developing countries.

At the Cancun climate change conference in 2010, developing countries were urged to submit more detail to the UNFCCC secretariat—the mitigation actions for which they are seeking support and the estimated emissions reductions, along with associated costs and the time frame for implementation (UNFCCC 2010: cl. 54).

A key clause in the Cancun Agreement is that internationally supported mitigation actions, for instance from the newly created Green Climate Fund, '…will be measured, reported and verified domestically and will be subject to international measurement reporting and verification' in accordance with the guidelines to be developed under the UN Framework Convention (UNFCCC 2010: cl. 61).

The message is clear—if developing countries seek rewards for REDD actions, they will need to undertake work to measure, report and verify (MRV) emissions reductions and cost their proposals.

## Papua New Guinea and REDD

Land use, land-use change and forestry (LULUCF) contribute about 90% of Papua New Guinea's (PNG's) total emissions of C, selective harvesting being a major contributor. Under business-as-usual (BAU), the cumulative contribution of selective harvesting, for both domestic consumption and export, during 2010–20 will be about 500 million tonnes (Mt) of carbon dioxide ($CO_2$) (Hunt 2010). There is therefore potential for PNG to make a substantial contribution to global abatement efforts, in the near term, through REDD.

A reduction in selective harvesting is the most practical means of substantially mitigating PNG's carbon emissions, but it is not the only means. There is already a Logging Code of Practice (LCP) in force that is aimed at minimising the damage to forest in logging operations (PNGFA and DEC 1996), but its application is very patchy. The reduction in emissions from low-impact logging (LIL) should therefore be the difference between emissions under the LCP and emissions under LIL, rather than the much larger difference between emissions under present destructive practices and LIL; otherwise, PNG could be rewarded under REDD+ for not adhering to the LCP.

The cost per tonne (t) of $CO_2$ abatement from a reduction in selective logging is likely to be low compared with abatement costs through other means (Hunt 2010). This is important to PNG, which wants a minimal impact of REDD on its regional and national economies. It is also of importance to donors and international funding agencies, which are interested in getting value for money in their investments in mitigation actions. Moreover, if a market develops for C, with REDD credits eligible, the relative cost of PNG's credits could be attractive to investors.

The UNFCCC guidelines for measurement, reporting and verification (MRV) are yet to be developed. However, if PNG does formulate a REDD plan, a reduction in selective harvesting is likely to be its focus, and the work of Fox and Keenan (2011) will underpin PNG's MRV proposals compliant with UNFCCC guidelines.

## The importance of in-country research in estimating $CO_2$ emissions from land-use change and forestry

The importance of in-country research that instils reliability into estimates of the quantity of C taken up or released by land-use change and forestry (LUCF) is illustrated by the confusion that has surrounded the estimation of emissions due to LUCF in PNG (Filer et al. 2009; Shearman et al. 2009). It is also illustrated by the problems that have afflicted even the most comprehensive estimates of greenhouse gas emissions from LUCF caused by deforestation in tropical Asia and South America for a particular year. Houghton (2005) explains how errors are likely, stemming from the errors in estimation of biomass lost per hectare through land conversion, as well as from errors in estimation of forest hectares converted.

The unreliability of estimates is illustrated by reference to estimates for 2000 compared with those for 2005 for PNG's emissions. The World Resources Institute (WRI 2009) estimated that emissions in PNG, including from LUCF, in 2000 totalled 146 Mt of $CO_2$. WRI (2011) revised downwards its 2005 estimates for PNG emissions, including LUCF, to 48.6 Mt of $CO_2$. PNG's international ranking in the emissions stakes thus fell from 9th to 70th. (Downward revisions in WRI's 2008 tables of emissions by country have also been applied to Indonesia and other tropical forested countries.) However, there is no evidence that PNG reduced emissions threefold over this period. And the veracity of even this new estimate is in doubt, given that Fox and Keenan (2011) estimate PNG's $CO_2$ emissions from selective harvesting alone for 2005 to be 52.8 Mt.

## Some methodological considerations in projecting $CO_2$ abatement by reducing LUCF emissions

In estimating the abatement of emissions to be achieved, it is necessary to include not only the abatement achieved by the action but also what would have occurred without the action; that is, under BAU.

### *Estimating emissions abatement by REDD*

The emissions reduction achieved on an annual basis is the difference between emissions with the project and emissions without the project, as follows in equation (1):

$$A_n = Ew_n - Ewo_n \qquad (1)$$

where:
$An$ = abatement of emissions in year $n$
$Ew_n$ = emissions with REDD in year $n$
$Ewo_n$ = emissions without REDD (or BAU) in year $n$.

And cumulative abatement is as follows (equation (2)):

$$CA = \sum_{n=1}^{y}(Ew_n - Ewo_n) \qquad (2)$$

where:
$CA$ = cumulative abatement from REDD
$n$ = years 1 to $y$.

The methodology, in the case of PNG selective harvesting for export, is illustrated through Figures 1 and 2.

In Figure 1, $CO_2$ emissions from selective harvesting fall sharply after its cessation at the beginning of 2012. They become negative in 2015 as the effect of the rate of sequestration of C (1 t C = 3.67 t $CO_2$) in regrowth overtakes the reduction in $CO_2$ emissions from collateral damage to the forest plus the harvesting process and log removal.

The emissions reduction achieved in any one year during 2012–25 is the difference between the 'with REDD' curve and the 'without REDD' (i.e. the 'BAU') curve in this period. The modelling assumes that the supply of merchantable logs ceases in 2025 and, with it, the BAU emissions (Hunt 2010).

The cumulative reduction in emissions achieved in Figure 2 is the summed difference between 'with REDD' and 'BAU' for 2012–25. The cumulative abatement from the cessation of selective harvesting for export, is almost 400 Mt of $CO_2$ by 2020, and approaches 700 Mt in 2025.

The approach has been to demonstrate the impact on $CO_2$ emissions of a cessation in selective harvesting for export in 2012. However, the model can be used just as well to assess the impact of a partial reduction in selective–harvesting.

## Modelling of emissions and emission targets

Developed countries have been required to reduce their emissions against 1990 levels by 2010–12 under the first commitment period of the Kyoto Protocol. While developing countries have been under no such obligation, it has become obvious that they will be responsible for an increasing, and dominant, share of emissions in the future (Garnaut 2011). Effective global action in mitigating climate change will be impossible without developing-country participation.

Most of the pledges of developing countries after the Copenhagen Accord have been in the form of expected reductions against future BAU levels of emissions. (PNG's pledge can be found at Conrad (2010).) The relative commitments by developing countries can be compared using different parameters, including absolute change in expected emissions, change in expected emissions per capita, and change in expected emissions intensity of countries' economies (Jotzo 2010).

There is a natural tendency for developing countries to overestimate their BAU emissions projections and therefore the pledged percentage cut. For this reason, the emissions intensity of economies ($CO_2$/gross domestic product) might well be adopted as an alternative criterion to reductions against BAU (Jotzo 2010).

Whatever methods are adopted to measure a country's contribution to global cuts in emissions, it is clear that a reduction in selective harvesting is the most practical means by which PNG can make a substantial contribution (Hunt 2010). To be credible, PNG's estimates of its future contribution must be underpinned by research—hence, the importance of the work of Fox and Keenan (2011).

## Perspectives on REDD and decision-making by donors and recipients

A precondition for a global market for C to supersede the Kyoto Protocol after 2012 is collective action on quantitative cuts by major emitting countries. If the market is to include REDD schemes, a tonne of C generated by REDD must equal a tonne of C generated by a reduction in the use of fossil fuels or other abatement measures (see Hunt (2011) for conditions for the formation of a market that includes C from REDD).

But the collective action that would enable the formation of a C market is absent and, given the reluctance by large emitting nations to commit to quantitative cuts, the formation of a market is not an immediate prospect. In the absence of a C market, and to enable REDD schemes to proceed, funds have been pledged by developed countries for non-market schemes in which individual developed countries, or the Green Climate Fund, engage directly with tropical developing countries in the transfer of REDD funds. It is inevitable that the donor will need to be satisfied that the deployment of REDD funds will have a positive socioeconomic outcome.

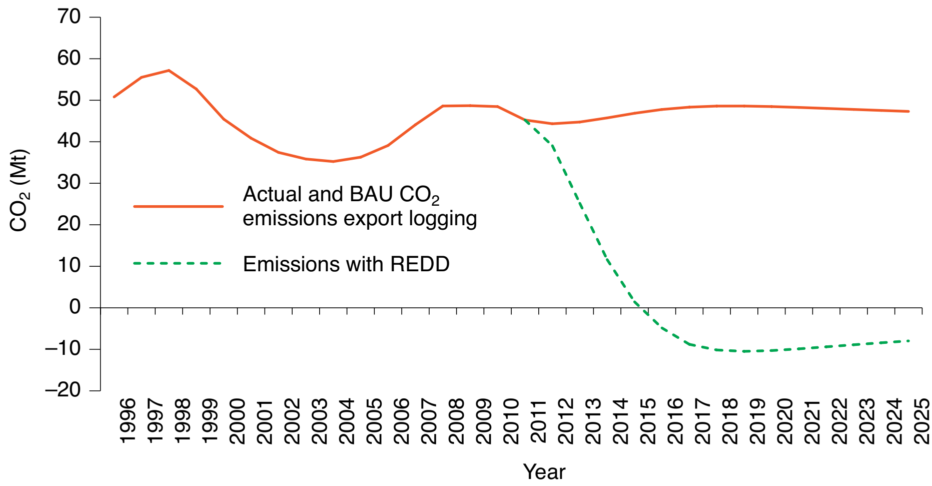


**Figure 1.** $CO_2$ emissions, selective harvesting for export, with and without REDD, Papua New Guinea. Source: Hunt (2010)

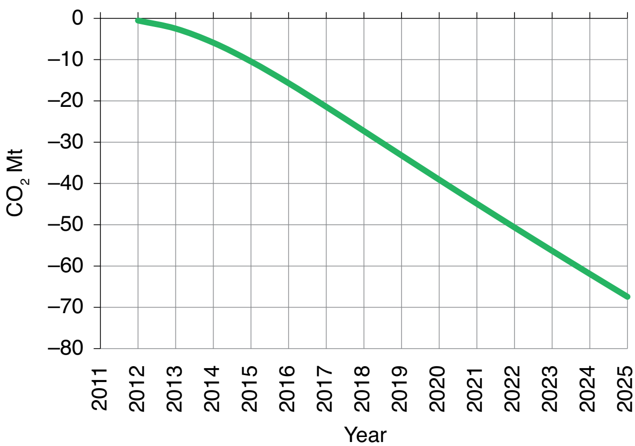


**Figure 2.** Cumulative $CO_2$ emissions abatement with cessation of selective harvesting for export in 2012, Papua New Guinea. Source: author's calculations

The donor countries have signalled their willingness to enter into bilateral REDD arrangements with developing countries, even though common rules for MRV have not yet been adopted. These prospective donors will be relying, to some extent, on developing-country assessments of emissions reduction potential and associated costs. They will inevitably choose to financially support REDD where risks to their investment and the cost of C abated are relatively low.

The funds approach to REDD is therefore fundamentally different to a market approach, where the buyer of a tonne of C has no interest in how the seller uses the proceeds. Moreover, the buyer in a market scheme assumes that any risk-associated C in the market has been equalised by the application of protocols governing its source, whether sequestered or abated.

The risks in funds-based schemes are many and varied (as discussed by Hunt (2010) for the case of PNG), but a principal one is that the level of abatement might fall short of expectations due to inaccurate estimate of past or future emissions. In PNG's case there are now detailed estimates of $CO_2$ abated by a reduction in selective harvesting, and the researchers have recommended that this methodology be improved as more information becomes available (Fox and Keenan 2011).

Value for money is indicated by the cost per tonne of $CO_2$ abatement achieved. It has also been shown by economic research that REDD based on a reduction in selective harvesting in PNG will potentially be a lower cost when compared with costs of abatement by, for example, reducing oil palm establishment, because the opportunity costs are lower (Hunt 2010).

PNG's perspective on REDD is rather different from that of prospective REDD donors. First, PNG must be concerned that there is a net benefit to the economy of the country by the substitution of REDD funds for economic activity generated by timber harvesting, including foregone opportunity costs. Second, it must ensure that the distribution of REDD funds is equitable between stakeholders.

Figure 3 shows the total export income for PNG from raw logs for export, actual and BAU projected to 2025, and for individual stakeholders. Log export income is expect to rise and plateau after the downturn due to the global financial crisis. The stakeholders are harvesting companies, government and landowners. Because the profits of harvesting companies are uncertain, Figure 3 shows only harvesting-company gross income.

The third crucial concern of the PNG Government must be that landowners are not disadvantaged. REDD funds would be substituted for royalties and development benefits; and the loss of regional employment generated by export harvesting must also be addressed. This concern will be shared by prospective donors, who will wish to see an improvement in socioeconomic status of landowners as a result of

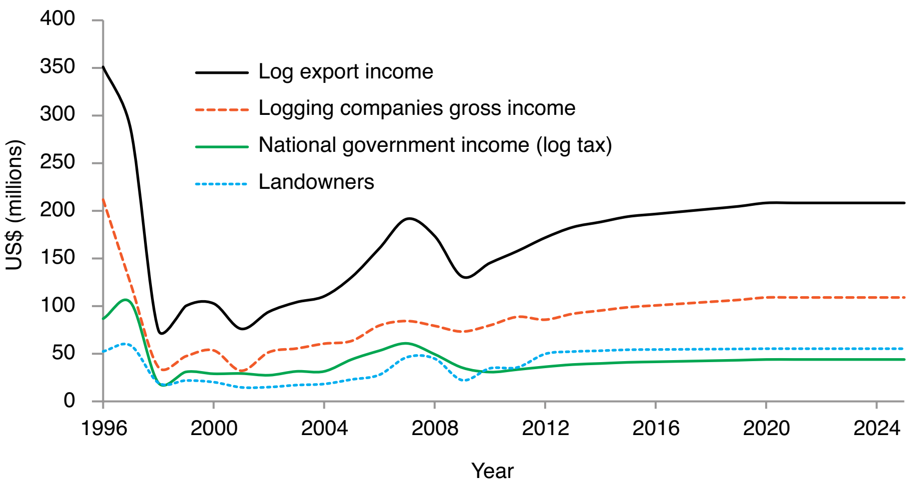


**Figure 3.** Stakeholder income from raw log exports, actual to 2008, BAU projected to 2025, Papua New Guinea. Source: author's calculations

REDD. Hunt (2010) recommends more research into the means by which REDD payments could benefit the economy in general and landowners in particular.

It should be noted that there may be economic opportunity costs of REDD, other than profits and revenues of stakeholders, that need to be accounted for. Costs that might easily be overlooked are the provision of direct services and infrastructure by companies; for example, on medical services and on roads, bridges and wharves. The economic impact of the spending of stakeholders is another example. In PNG, palm oil companies spend large sums on regional goods and services. Harvesting companies spend less, but their expenditure on labour could be important locally. Such spending has a multiplier effect, with the recipients of the spending by companies themselves spending a proportion on local goods and services, and so on.

REDD compensation policy should aim to generate economic activity that is at least equal to, or greater than, the economic activity that it replaces.

### Estimating opportunity costs of REDD

There are two important elements of decision-making in REDD:

- the identification of costs, both overall and to individual stakeholders, of a REDD program
- the relative costs and benefits of taking alternative actions under REDD.

It is emphasised that, for equitable decision-making with respect to the payment of compensation for the opportunity costs incurred under a REDD program, it is necessary to compensate affected stakeholders commensurate with the costs that they will incur. A note on the methodology for estimating opportunity costs follows.

In estimating the cost of REDD, the model is the same as for estimating the net abatement of $CO_2$ by REDD (equation (1)); that is, 'with project' less 'without project'. The difference between incomes with REDD and incomes without REDD (BAU income) is shown in equation (3):

$$OCw_n = \{Yw_n(SA_n+SB_n \ldots +SZ_n)\} - \{YBAU_n(SA_n+SB_n \ldots +SZ_n)\} \quad (3)$$

where:
$OCw_n$ = opportunity cost with REDD in year $n$
$Yw_n$ = income with REDD in year $n$
$YBAU_n$ = BAU income in year $n$
$SA_n$, $SB_n$, $SZn$ = stakeholders' incomes in year $n$.

It should be noted that the income with REDD might contain some 'hidden' income. For example, in the case of a cessation of harvesting, landowners might compensate for the loss of royalties by increasing small-scale cash cropping and subsistence agriculture. However, valuing such activity is very difficult, and it may well be necessary to set income with REDD ($Yw$ in equation (3)) at zero.

To compare the costs of different REDD actions—for example, a reduction in selective harvesting versus a reduction in oil palm establishment—the present value of the opportunity costs per tonne of $CO_2$ abated is derived for each of the different actions by dividing the opportunity cost by the abatement achieved, as in equation (4):

$$OCCt = \{\sum_{n=1}^{y} OC_n/(1+r)^n\}/\{\sum_{n=1}^{y} Ct_n/(1+r)^n\} \quad (4)$$

where: $OCCt$ = opportunity cost per tonne of $CO_2$ abated by REDD action
$OC_n$ = opportunity cost of REDD action in year $n$
$Ct_n$ = tonnes of $CO_2$ abated by REDD action in year $n$
$r$ = discount rate.

The recommended methodology to obtain the cost per tonne of $CO_2$ abated in equation (4) is to divide the discounted stream of costs by the discounted stream of abatement, as discussed in Richards and Stokes (2004). For more detail on methodologies for the derivation of opportunity costs to stakeholders, as well as overall costs in the case of selective harvesting for export and oil palm establishment in PNG, together with the relative costs of REDD per tonne of $CO_2$ abated, see Hunt (2010).

## Summary and conclusions

Developing countries are required to report their greenhouse gas abatement proposals, and associated costs, to the UNFCCC secretariat. A high proportion of PNG's emissions are from LUCF. Given the level of measurable emissions from selective harvesting, it is likely to be central to PNG's proposals to reduce emissions from LUCF.

The credibility of REDD proposals is crucial: they will be searchingly scrutinised by prospective donors to international funds for REDD or purchasers of REDD credits. In the case of applications to international funds, REDD proposals will be subject to international rules for MRV.

This chapter has set out to clarify central issues in REDD reporting and decision-making. It has done this by explaining the international rules associated with REDD that PNG must abide by, and by detailing the methodology for the estimated abatement of $CO_2$ emissions associated with REDD, and the costing of REDD proposals.

To be equitable and effective, compensation must be based on incomes foregone, or the opportunity costs, to stakeholders. Developing the principles and formulas for distributing benefits between government, industry and the community will be a political challenge. The methodology for the estimation of opportunity costs is detailed. The existence of costs other than direct costs to stakeholders has been noted. The methodology is also set out for the comparative costing of different proposals for emissions abatement.

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# Scenario analysis of selective harvesting, carbon dioxide emissions and REDD+ in Papua New Guinea

**David C. Coote[1*] and Julian C. Fox[1]**

*Abstract*

Building on the work of Fox and Keenan in these proceedings, we develop scenario analysis capability for modelling carbon dioxide ($CO_2$) emissions, and possible emissions reductions and REDD+ financial returns, from a Papua New Guinea selective-harvesting model. The approach taken is to compare a $CO_2$ emissions abatement scenario due to changed forest management with a business-as-usual baseline based on current practices for the period 2008–28. The tools used are Microsoft® Excel with several Excel add-ins. The Excel 'what-if' tools are used to demonstrate goal-seeking, simple sensitivity analysis and the Scenario Manager capability. The Decision Toolworks tools SensIt and RiskSim (available as Excel add-ins) are used for more sophisticated sensitivity and Monte Carlo analysis. The model was used to produce $CO_2$ emissions abatement estimates for four simple scenarios: ceasing log export post 2011 and adding 250,000 $m^3$/year to local processing volumes (up to 1.5 $Mm^3$/year); reducing collateral damage in above- and below-ground biomass by 32% using reduced-impact harvesting methods; increasing regeneration success on selectively harvested areas from 75% to 100%; and increasing harvested volume utilisation from 33% to 66%. These forest-management scenarios resulted in cumulative $CO_2$ abatement estimates of up to 535 Mt/year. However, changed management practices as investigated here depend on improved forest governance, and there are likely to be additional operating expenses associated with forest harvesting.

## Introduction

Tropical forests play a crucial role in the global carbon (C) cycle through the storage and sequestration of C in living forest biomass. This has been recognised in international climate-change negotiations through the initiative to include reduced carbon dioxide ($CO_2$) emissions from deforestation and forest degradation (REDD+) coupled with the enhancement of forest C stocks through forest restoration, sustainable forest management and forest conservation in developing tropical countries (UNFCCC 2009). Papua New Guinea (PNG) has become a focus of the REDD+ initiative, providing an opportunity for the PNG Forest Authority and the forest industry to play an important role in climate-change mitigation by modifying their practices and ensuring the maintenance of C stock in forested areas.

Here, we explore scenarios for selective harvesting in PNG, and estimate possible $CO_2$ abatement. The tool chosen can also be used to estimate possible remuneration under a REDD+ mechanism. We use the selective harvesting and $CO_2$ modelling tool developed by Fox and Keenan (2011) to estimate emissions under several realistic scenarios for PNG, comparing baseline emissions under a business-as-usual (BAU) approach against emissions for the respective scenarios for the 20 years 2008–28. The four scenarios were: ceasing log export post 2011 while increasing local processing to 1.5 $Mm^3$/year;

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reducing collateral damage using reduced-impact logging (RIL); increasing regeneration success; and increasing harvested volume utilisation. We report the results as $CO_2$ emissions for these scenarios against $CO_2$-equivalent emissions, as the data we are working with are estimating and modelling $CO_2$ and do not include other greenhouse gases.

Scenario analysis and other what-if tools allow examination of model behaviour in a range of situations. Typically, an input parameter (or perhaps many) of the model is varied and the change in an output value of interest is examined. This can elicit useful information such as to which input parameter the model is most sensitive; that is, for a given percentage change to all input parameters, which one causes the most change in an output value. Once these data are available, management decisions may be made as to how an objective may be attained. For the work described here, this might be to maximise financial return or achieve a particular C emissions reduction figure. The underlying PNG selective-harvesting model developed by Fox and Keenan (2011) was not originally designed to offer scenario analysis; however, its application in this instance can increase the model's capacity to provide critical management information. A number of developing nations could potentially use this tool for REDD+ projects if the data informing the model input parameters are available; therefore, we have used cost-effective tools that could be sourced and installed on standard Windows personal computers.

# Methodology

## Tool selection

Selecting software tools can be a long and complicated process. For this work, Excel was used where possible. For further functionality, we wanted reliable tools that were low cost and available online for download, and which offered Monte Carlo and sensitivity analysis beyond Excel's inbuilt capabilities. The Decision Toolwork tools RiskSim and SensIt, developed by Professor Mike Middleton (http://www.treeplan.com/about.htm), met these criteria, with trial versions available for free and commercial versions available for US$49 for each tool. The tools have a wide range of customers (http://www.treeplan.com/customers.htm) and comprehensive documentation (http://www.treeplan.com/download.htm).

In 2008 the National Minister for Forests announced the phase-out of log exports from Papua New Guinea by 2010, and increased downstream processing of wood products. There is no evidence that this has occurred, and a great majority of forest harvesting in PNG is for log export. Shown is a rare example of downstream processing—a mill in Madang province in which timber is sawn for local housing and construction (Photo: Jim Grigoriou).

## Tool descriptions

Excel is the well-known spreadsheet published by Microsoft®. It was used to: generate simple sensitivity analysis using the Data Table feature; generate results using Goal Seek; and manage scenarios using the Scenario Manager. The Monte Carlo simulations presented in this report were generated by the RiskSim tool, and the extended sensitivity analysis was generated by the SensIt tool. Both tools install as Excel add-ins, and thorough documentation is available.

Once RiskSim is installed, the user specifies which input cells are to be varied, the probability distribution to use and the output cells in which to use the input values. The documentation provided with the tool describes this process in detail. The RiskSim tool was used to do Monte Carlo simulations on several input parameters of the model when implementing the cease-harvesting export scenario. The RiskSim simulations all assumed the normal probability distribution for the variables studied. For variables that are not normally distributed, the RiskSim tool offers other probability distributions such as discrete, Poisson and binomial. Other inputs could also be varied, both singly and in combinations, to give output distributions from those situations. The Monte Carlo portion of this work used data from Fox et al. (2011) for the parameters studied. For example, Fox et al. (2011) used a hierarchical Bayesian model to estimate parameters and valid 95% confidence intervals for mean primary forest above-ground live biomass (AGLB) of 137±9 (SD 4.5), mean selectively harvested forest AGLB of 62±18 (SD 9), and change in AGLB due to selective harvesting of 75±25 (SD12.5). If the timber volume is removed, then collateral damage is 70±20 (SD 10) (see Fox et al. (2011) and Fox and Keenan (2011) for a full explanation).

The SensIt tool is used in a similar fashion—to vary the values used in scenarios to calculate changes to the BAU baseline. This can be done for a single input or for all inputs.

### *Scenario Manager*

Excel's Scenario Manager provides the capability to store sets of values that can be used to set a collection of Excel cells to a known set of values. This stored set can be given a name for later identification and recall. For example, the spreadsheet contains a scenario called Baseline that contains the BAU baseline values for the Fox and Keenan (2011) model. To return to this known baseline, the input cells on the summary page can be set to the Baseline values.

### *Goal Seek*

The Excel Goal Seek feature can be used to set a target value for an output cell, and identify the value of an input value required to reach this target value. For example, using the cessation of export logs post 2011 scenario, to reach a total revenue of US$2 billion over the scenario time frame (20 years), the C price must be US$3.8/t.

### *Data Tables*

Excel's Data Tables can be used to do sensitivity analysis for a dependent variable by varying one or two variables. The example used calculates the variation of C revenue with changes in export harvesting volume and C price constant for each year of the scenario (Figure 1).

### *Spreadsheet worksheets*

The spreadsheet is split into a number of worksheets for ease of use and to assist with modular development.

### *Input cells*

The BaseParameters and Summary worksheets have a number of user-input cells by which the spreadsheet user can vary model input parameters. The summary worksheet has tickbox and option selections that allow the user to further tailor values used in calculating scenarios. While validation of

| Sensitivity analysis for carbon revenue varying carbon price and locally processed volume | | | | | | |
|---|---|---|---|---|---|---|
| | Carbon price used for each year of scenario (US$) | | | | | |
| | | 16 | 18 | 20 | 22 | 24 |
| Local processing volume change per year ($m^3$) | 150,000 | 9,093,035,325 | 10,229,664,741 | 11,366,294,157 | 12,502,923,572 | 13,639,552,988 |
| | 200,000 | 8,756,284,226 | 9,850,819,754 | 10,945,355,282 | 12,039,890,810 | 13,134,426,338 |
| | 250,000 | 8,557,621,149 | 9,627,323,793 | 10,697,026,436 | 11,766,729,080 | 12,836,431,724 |
| | 300,000 | 8,436,743,286 | 9,491,336,197 | 10,545,929,108 | 11,600,522,019 | 12,655,114,930 |
| | 350,000 | 8,335,154,047 | 9,377,048,303 | 10,418,942,559 | 11,460,836,815 | 12,502,731,071 |

**Figure 1.** Example output of sensitivity analysis showing the impact of variation in carbon price and local processing volume on carbon revenue

user inputs was not used in this work, it would be a simple matter to add this feature. Input spreadsheet cells are colour coded.

*BaseParameters worksheet*

There are over 20 input parameters identified for the model (see Fox and Keenan (2011) for full explanations). The spreadsheet was modified to allow all input parameters to be varied, providing maximum flexibility for scenario generation. The BaseParameters worksheet allows the user to enter parameters used in the BAU and scenario calculations. The inputs can be entered in the columns headed baseline and scenario. The scenario calculations will use the scenario value if set and the baseline value otherwise. The cells in the variation column can be used to set the amount by which the user wants to vary the BAU baseline values for analysis with the SensIt multiple input sensitivity analysis tool.

*Summary worksheet*

The Summary worksheet calculates a number of C emissions figures, and summarises them in a table (Figure 2). The summary table computes the difference between BAU and Scenario C figures for the years in the scenario of interest (e.g. Figure 2 shows results for the ceasing log export scenario), totals the differences in C emissions between BAU and Scenario, and computes a dollar value for the change in volume using a C price schedule (see Figure 4). The Scenario figure is subtracted from the BAU figure to give the value in the Abated column. Hence, a positive difference indicates a reduction in $CO_2$ emissions.

The Summary worksheet also calculates the net present value (NPV) of the C revenue over the scenario in 2008 dollars. The discount rate can be set by the user.

The log volume schedule (Figure 3) can be used to set the quantity of logs exported and processed locally. Log exports cease after 2011 if that Scenario tickbox is selected. The change in volume for locally processed logs is added cumulatively to each year to modify the BAU figure up to a user-specified maximum if that action is selected using the Scenario tickbox. As shown in Figure 3, we have set the model to cease log exports after 2011 and to increase local processing volumes by 250,000 m$^3$/year up to 1.5 Mm$^3$/year.

The C price schedule (Figure 4) can be used to set the C price used for the years of the scenario as either a constant price, a price rising at a constant percentage each year from an initial figure (both values can

**Results summary**

| | | | | | | Discount rate |
|---|---|---|---|---|---|---|
| | | | | | | 10% |
| **Year** | **BAU $CO_2$ (t)** | **Scenario $CO_2$ (t)** | **Abated (t)** | **Carbon price (US$)** | **Total (US$)** | **NPV (US$)** |
| **2009** | 71,501,879 | 71,501,879 | 0 | 20 | 0 | 0 |
| **2010** | 65,680,872 | 65,680,872 | 0 | 20 | 0 | 0 |
| **2011** | 63,850,276 | 54,255,678 | 9,594,598 | 20 | 191,891,958 | 144,171,268 |
| **2012** | 64,993,547 | 40,074,703 | 24,918,845 | 20 | 498,376,890 | 340,398,122 |
| **2013** | 66,896,609 | 28,157,428 | 38,739,182 | 20 | 774,783,638 | 481,079,681 |
| **2014** | 68,628,617 | 21,285,024 | 47,343,592 | 20 | 946,871,844 | 534,484,471 |
| **2015** | 70,096,470 | 19,804,230 | 50,292,240 | 20 | 1,005,844,803 | 516,157,427 |
| **2016** | 71,070,168 | 20,438,212 | 50,631,956 | 20 | 1,012,639,113 | 472,403,620 |
| **2017** | 71,736,342 | 22,765,025 | 48,971,318 | 20 | 979,426,354 | 415,372,384 |
| **2018** | 72,234,135 | 24,797,365 | 47,436,770 | 20 | 948,735,398 | 365,778,566 |
| **2019** | 72,643,550 | 26,223,466 | 46,420,084 | 20 | 928,401,681 | 325,399,125 |
| **2020** | 72,997,671 | 27,124,862 | 45,872,809 | 20 | 917,456,181 | 292,329,813 |
| **2021** | 73,230,029 | 27,600,994 | 45,629,034 | 20 | 912,580,687 | 264,342,119 |
| **2022** | 73,284,726 | 27,863,776 | 45,420,950 | 20 | 908,419,001 | 239,215,115 |
| **2023** | 70,526,567 | 28,012,074 | 42,514,493 | 20 | 850,289,852 | 203,552,630 |
| **2024** | 57,759,578 | 28,100,727 | 29,658,852 | 20 | 593,177,035 | 129,092,605 |
| **2025** | 39,482,881 | 28,158,839 | 11,324,043 | 20 | 226,480,852 | 44,808,029 |
| **2026** | 22,426,183 | 28,201,471 | −5,775,288 | 20 | −115,505,762 | −20,774,727 |
| **2027** | 10,015,969 | 28,234,718 | −18,218,749 | 20 | −364,374,973 | −59,578,220 |
| **2028** | 2,338,155 | 28,261,560 | −25,923,406 | 20 | −518,468,115 | −77,066,982 |
| **Total** | **1,181,394,225** | **646,542,903** | **534,851,322** | | **10,697,026,436** | **4,611,165,048** |

BAU = business-as-usual; NPV = present net value

**Figure 2.** Summary table showing business-as-usual and scenario data

be set by the user), or a price for each year input by the user. The toggle facility allows the user to select the desired option. As shown in Figure 4, we have set the model to use a constant price of $20/t for $CO_2$.

# Results

## Simple scenarios

The model was used to produce abated $CO_2$ emissions figures for four simple scenarios: ceasing log export after 2011 and adding 250,000 $m^3$/year (capped at 1.5 $Mm^3$/year) to local processing volumes; reducing collateral damage in above- and below-ground biomass by 32% using RIL; increasing regeneration success on selectively harvested areas from 75% to 100%; and increasing harvested volume utilisation from 33% to 66%.

This produced the following estimated abated $CO_2$ emissions for 2011–28 (Table 1).

## RiskSim Monte Carlo analysis

### *Collateral damage*

The collateral damage input parameter was varied according to a normal distribution with mean 70 (tC/ha) and standard deviation 10. This was done by replacing the scenario input value for collateral damage in the BaseParameters worksheet with the function call RANDNORMAL(70, 10). The simulation was run 500 times to produce a histogram (Figure 5).

### *Primary forest carbon*

The input parameter carbon fraction of AGLB in PNG primary forest (tC/ha) was varied according to a normal distribution with mean 137 (tC/ha) and standard deviation 4.5. This was done by replacing the scenario input value for carbon fraction in the BaseParameters worksheet with the function called RANDNORMAL(137, 4.5). The simulation was run 500 times to produce the histogram (Figure 6).

| Log volume schedule | | | | |
|---|---|---|---|---|
| | Export volume ($m^3$) | | Locally processed volumes ($m^3$) | |
| | | | Annual change | Maximum |
| | | | 250,000 | 1,500,000 |
| Year | BAU | Scenario | BAU | Scenario |
| 2009 | 2,051,132 | 2,051,132 | 483,750 | 483,750 |
| 2010 | 2,436,014 | 2,436,014 | 483,750 | 483,750 |
| 2011 | 2,576,014 | 0 | 483,750 | 483,750 |
| 2012 | 2,616,014 | 0 | 483,750 | 733,750 |
| 2013 | 2,656,014 | 0 | 483,750 | 983,750 |
| 2014 | 2,714,246 | 0 | 483,750 | 1,233,750 |
| 2015 | 2,742,302 | 0 | 483,750 | 1,483,750 |
| 2016 | 2,770,357 | 0 | 483,750 | 1,500,000 |
| 2017 | 2,798,413 | 0 | 483,750 | 1,500,000 |
| 2018 | 2,826,468 | 0 | 483,750 | 1,500,000 |
| 2019 | 2,854,524 | 0 | 483,750 | 1,500,000 |
| 2020 | 2,882,579 | 0 | 483,750 | 1,500,000 |
| 2021 | 2,882,579 | 0 | 483,750 | 1,500,000 |
| 2022 | 2,882,579 | 0 | 483,750 | 1,500,000 |
| 2023 | 2,172,579 | 0 | 483,750 | 1,500,000 |
| 2024 | 0 | 0 | 483,750 | 1,500,000 |
| 2025 | 0 | 0 | 483,750 | 1,500,000 |
| 2026 | 0 | 0 | 483,750 | 1,500,000 |
| 2027 | 0 | 0 | 483,750 | 1,500,000 |
| 2028 | 0 | 0 | 483,750 | 1,500,000 |

BAU = business-as-usual

**Figure 3.** Log volume schedule

| Carbon price schedule | | | |
|---|---|---|---|
| Carbon price annual increment (%) | | 10% | |
| | Carbon value/tonne (US$) | | |
| | Constant price | 10.0% / year price increment | Market price estimate |
| Year | | | |
| 2009 | 20.0 | 20.0 | 10.0 |
| 2010 | 20.0 | 22.0 | 20.0 |
| 2011 | 20.0 | 24.2 | 20.0 |
| 2012 | 20.0 | 26.6 | 20.0 |
| 2013 | 20.0 | 29.3 | 30.0 |
| 2014 | 20.0 | 32.2 | 30.0 |
| 2015 | 20.0 | 35.4 | 40.0 |
| 2016 | 20.0 | 39.0 | 30.0 |
| 2017 | 20.0 | 42.9 | 30.0 |
| 2018 | 20.0 | 47.2 | 50.0 |
| 2019 | 20.0 | 51.9 | 50.0 |
| 2020 | 20.0 | 57.1 | 51.0 |
| 2021 | 20.0 | 62.8 | 52.0 |
| 2022 | 20.0 | 69.0 | 53.0 |
| 2023 | 20.0 | 75.9 | 54.0 |
| 2024 | 20.0 | 83.5 | 55.0 |
| 2025 | 20.0 | 91.9 | 56.0 |
| 2026 | 20.0 | 101.1 | 57.0 |
| 2027 | 20.0 | 111.2 | 58.0 |
| 2028 | 20.0 | 122.3 | 59.0 |

**Figure 4.** Carbon price schedule

**Table 1.** Abated $CO_2$ emissions for several scenarios

| Scenario | Abated $CO_2$ emissions (Mt) |
|---|---|
| Ceasing log export post 2011 | 535 |
| Reduced impact logging | 368 |
| Increasing regeneration success | 90 |
| Increasing harvested volume utilisation | 1 |

## SensIt sensitivity analysis

*Removals per hectare*

Using SensIt's single input sensitivity analysis capability, the timber volume removal scenario input value was varied between 10 and 20 m$^3$/ha. The change in $CO_2$ emissions was compared with the BAU (Figure 7).

*Sensitivity to all inputs*

The 'Many inputs, One output' SensIt capability was used to generate a tornado chart showing the change in BAU C emissions with a ±10% change in all the model inputs. The results are presented in Figure 8).

# Discussion

The tornado chart (Figure 8) reveals the input parameters to which $CO_2$ BAU emissions are most sensitive for a ±10% change. The volume of timber removed per hectare of selective harvesting is the most important variable in the $CO_2$ emissions model. In the absence of historical spatial information on land cover and land-cover change for PNG, Fox and Keenan (2011) estimate $CO_2$ emissions based on an assumption of average timber volume extracted of 15 m$^3$/ha under a selective-harvesting regime. This analysis has revealed that $CO_2$ emissions calculations are highly sensitive to this estimate. It is recommended that future work use remote sensing data sources to more explicitly and accurately identify areas affected by selective harvesting. Another approach to reduce uncertainty in this estimate is to undertake concession-level analysis of net available area, net volume and volumes of roundwood export and locally processed timber. The timber removed per hectare of selective harvesting will vary for different concessions according to the density of marketable timbers, the market requirements of the operators and site conditions such as slope, soil type and watercourses.

$CO_2$ emissions estimates are also very sensitive to changes in the collateral damage per hectare. Collateral damage due to selective harvesting (70 tC/ha) was estimated in the analysis of Fox et al. (2011) based on analysis of permanent sample plots (PSPs). The PSP dataset consists of 121 plots in selectively harvested forest and 12 plots in primary forest. Although the sample of primary forest plots is small, we used hierarchical Bayesian models to estimate change in C stock due to selective harvesting. This provided an estimate of the displacement of AGLB to collateral damage and wood products. However, the comparison in Fox et al. (2011) is unbalanced and unmatched—there were far more observations in selectively harvested forest, and plots were not designed for this comparison. Matched plots in adjoining primary and selectively harvested forest would provide a more valid comparison. Nevertheless, an initial estimate of 55% reduction in AGLB is a useful indicative figure for calculations of reductions in forest C due to commercial selective harvesting in PNG. Similar reductions have been observed elsewhere: Lasco et al. (2006), Tangki and Chappell (2008), Feldpausch et al. (2005) and Gerwing (2002) all observed 50% reductions in AGLB in the Philippines, Borneo, southern Amazon and Brazilian Amazon respectively. Future work should examine paired PSPs in primary and selectively harvested forest to confirm estimates of collateral damage from Fox et al. (2011). There also needs to be further investment in establishing PSPs in primary forest.

The $CO_2$ emissions model was also sensitive to the percentage area of successful regeneration. This is due to regrowth forest actively sequestering $CO_2$, in contrast to unsuccessful regeneration that degrades and releases $CO_2$. Post-harvest treatment to improve regeneration success could therefore improve the C balance sheet of selective harvesting. The sensitivity analysis also revealed other important variables in the $CO_2$ emissions model of Fox and Keenan (2011) that require further examination; for example, the C fraction of AGLB in primary (137 tC/ha) and selectively harvested (62 tC/ha) forest (Fox et al. 2011); the below-ground to above-ground biomass ratio (0.37; IPCC 2006); the ratio of area deforested to selectively harvested area (0.15; Pulkki 1997); and

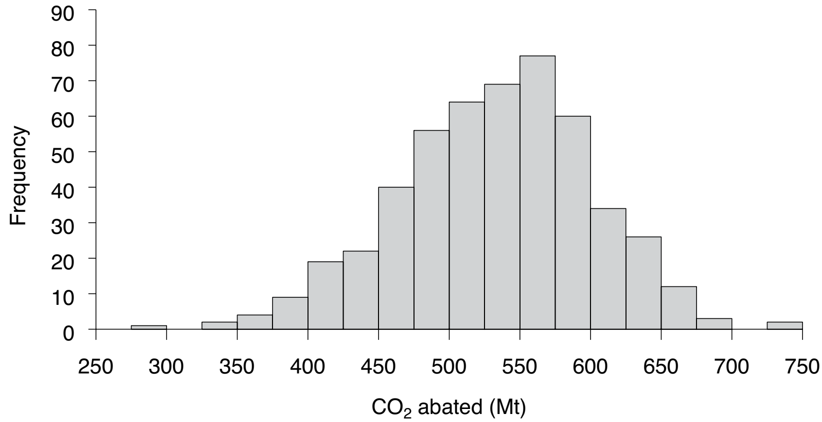


**Figure 5.** Histogram for difference in $CO_2$ emissions for collateral damage using Monte Carlo simulation with mean 70 tC/ha and standard deviation 10 tC/ha

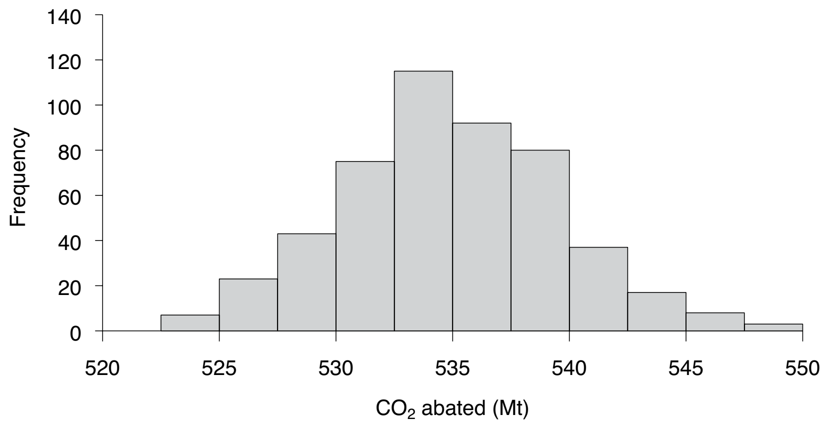


**Figure 6.** Histogram for difference in $CO_2$ emissions for primary forest carbon losses in deforested areas using Monte Carlo simulation with mean 137 tC/ha and standard deviation 4.5 tC/ha

the successful regrowth rate parameter (–16; Fox and Keenan 2011). There is a clear imperative for further field measurement of the C dynamic of selective harvesting that will reduce the uncertainty in some of these parameters, and contribute to defensible C emissions estimates from forest disturbance in PNG.

High $CO_2$ emissions from selective harvesting, coupled with large areas subject to harvesting, result in very large national emissions estimates that result in very large monetary estimates when converted to possible remuneration at different C pricing schedules under REDD+. For a particular C price, the return from REDD+ will show sensitivity to input parameters dependent on the interplay between the baseline scenario and the REDD+ scenario modelled. Monetary estimates under REDD+ will be realised only with drastic improvement of forest-management practices in PNG. Indeed, realising the scenarios explored here may be very expensive. For example, a large emissions reduction results from the implementation of RIL. Some of the challenges and costs associated with RIL implementation in PNG are briefly considered below.

RIL, first introduced in 1993, was designed in Queensland, Australia, but later improved by the United Nations Food and Agriculture Organization (FAO) to be used by tropical developing countries (Putz et al. 2008). Putz and Pinard (1993) argue that RIL can be used to reduce forest damage in selective-harvesting operations that can increase C retention in forest. However, RIL is broader than improving C retention, and encompasses well-planned and controlled timber-harvesting operations to reduce the impact on the environment. To realise the C retention benefits of RIL, many aspects of selective harvesting need to be improved; for example, pre-harvesting inventory; development of a forest-management plan, including unit designation; assignment of annual coupes, road and landing planning, and layout and construction; preharvest stand mapping and felling planning; and felling technique and post-harvest assessment (Sist et al. 1998; Tropical Forest Foundation 2007). The biggest constraint to RIL implementation is the additional cost. This issue has been expressed by tropical forest managers and is likely to have resulted in slow adoption (Putz et al. 2000). To implement RIL, forest-harvesting companies would need to invest in new, lower impact equipment, provide training for workers, adopt new operational procedures and hire supervisors to monitor the planning and implementation of new methods (Putz et al. 2000). Moreover, RIL implementation normally reduces the net area harvested and the volume removed. While there may be some savings in improved planning, reduced fuel costs, and wear and tear on equipment, RIL can significantly decrease the financial benefit of commercial forest harvesting (Putz and Pinard 1993). Beyond the balance sheet of harvesting companies, RIL requires improved forest governance and management. These challenges should not be underestimated in PNG. Indeed, the PNG Logging Code of Practice (1996) already includes some of the RIL guidelines for selective harvesting in PNG, but this is currently poorly implemented and poorly policed (Hunt 2011).

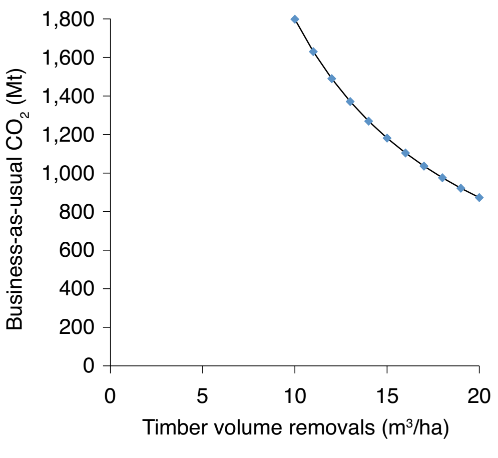


**Figure 7.** Variation of baseline $CO_2$ emissions with timber volume removals per hectare

It would be possible to extend the model we present here to incorporate costs associated with a change in input parameters. This would allow identification of the most profitable actions under a REDD+ approach. Where constraints such as insufficient trained personnel or inadequate annual budgets exist, the model could include an optimisation capability that would be used to generate the optimal financial return for a particular year or over the period of the scenario, by selecting management actions that vary the input parameter for a particular objective. Obviously, quantitative data for the relevant costs would either need to exist, be estimated from comparable environments or be established by new research. The model could also be extended to include opportunity costs such as those calculated by Hunt (2011). This would further inform management planning to produce optimal outcomes.

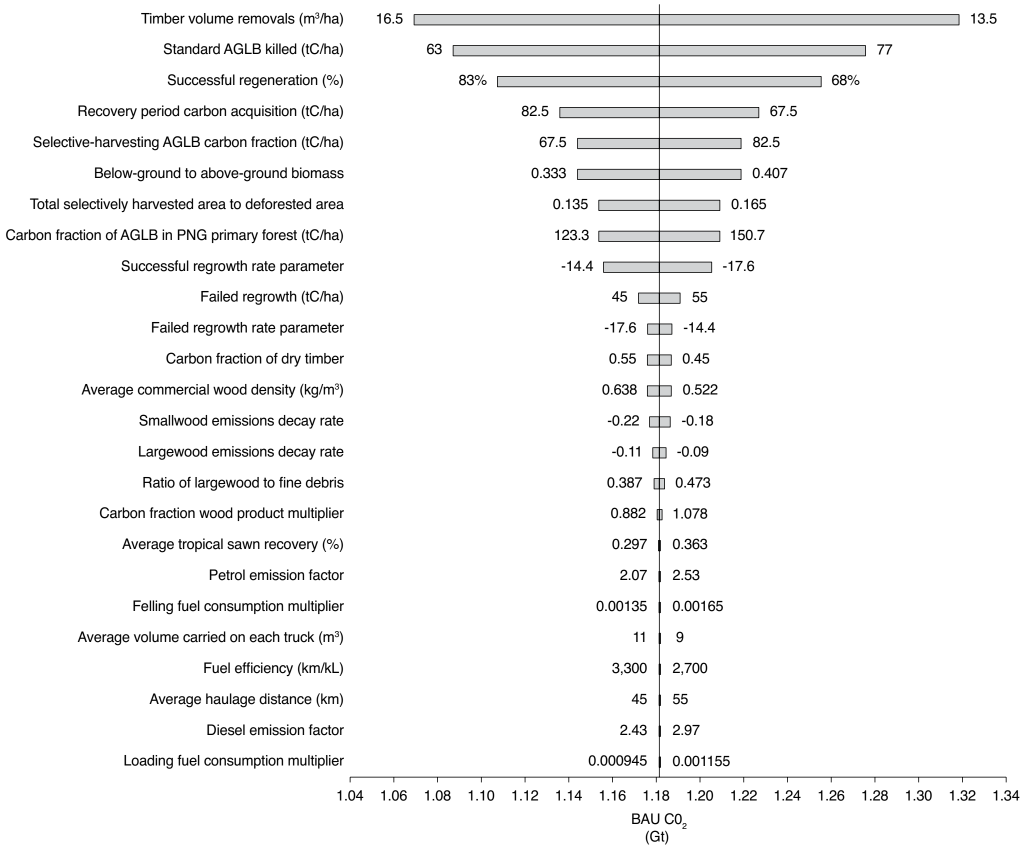


**Figure 8.** Tornado chart for Papua New Guinea REDD carbon inputs showing variation of business-as-usual (BAU) $CO_2$ emissions with model changes

Excel has a number of what-if tools that can provide valuable information when used in forests and $CO_2$ emissions modelling. The tools from Decision Toolworks were easy to obtain, install and use. They provide an inexpensive capability to quickly generate sensitivity analysis and Monte Carlo simulations. NPV is a standard technique with well-known features. Adding flexible schedules for C pricing and log volumes facilitates what-if scenario analysis.

The model is now available for use in REDD+ modelling of PNG forests. For other countries where research has identified values for the parameters used in this model, the tool could be used for REDD+ modelling with minimal modification. Using appropriate, cost-effective commercially available tools allows rapid development of sustainable forest-management models.

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# Decision-making

# Production and supply options for community forest enterprises in Papua New Guinea

**Jim Gigoriou[1,*], Cossey, K. Yosi[1] and Rodney J. Keenan[1]**

*Abstract*

This study determined what production and supply model is most appropriate for community-run portable sawmills in Papua New Guinea that are processing less than 1,000 cubic metres of logs per year. This technical analysis found that milling green boards for local buyers, with exporting occurring only via specialised cooperative organisations such as central marketing units, was the preferred approach. When direct exporting or value-adding activities such as timber drying or milling takes place, the processing of at least 4,000 cubic metres of logs per year is required to achieve consistent profitability. Forest certification is a significant cost that reduces profitability and is currently not expected by buyers in Papua New Guinea. Unprofitable community-run portable sawmills are either located at a great distance from their buyers, or appear to lack sufficient business development skills to establish a viable business model that creates value for customers in a profitable way.

## Introduction

This study examines the financial viability of community-run portable sawmill operations in Papua New Guinea (PNG). A financial model is used to test different production options, based on the harvest and processing of up to 1,000 cubic metres ($m^3$) of logs annually with a single portable sawmill. The financial viability of value-adding through drying and planing of timber was also assessed.

This technical analysis has been undertaken to understand the factors that make community sawmilling profitable, and what barriers are inhibiting the many uneconomic small sawmills presently operating in PNG.

### Portable sawmills in PNG—historical and current perspectives

Small-scale sawmilling in PNG commenced in the mid 1970s when church groups situated in remote areas used them to provide communities with building materials. By the early 1980s, portable sawmills that could be carried into the forest by four men had been designed. Subsequently, there was rapid growth in the number of mills in use, with subsidies from development agencies or funding provided by government for communities to purchase mills.

There are few data on the number of portable sawmills in operation or their production levels. In 1993, 350 of the estimated 1,500 portable sawmills nationwide were surveyed. It found that operators were harvesting an average of three to four trees per week, and were employing seven people.

In terms of communities practising sustainable forestry, there are an estimated 110 operations. They are engaged in the processing and sale of timber from their forests to supply building materials to their community, and so earn wages to sustain livelihoods and generate profits.

Portable sawmills usually operate near existing roads, often in areas where industrial harvesting has previously taken place, where existing harvesting roads and tracks can be used to access the resource and transport sawn boards to market. These operations process both standing trees and logs that have been felled yet rejected by loggers. Mechanisation (i.e. truck, tractor)

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Portable sawmilling in traditional dress in Simbu province, Papua New Guinea. Certification would require minimum safety standards that are clearly not satisfied in this instance (Photo: Julian Fox).

to reduce the manual handling of heavy material is a primary requirement of communities.

A community's decision to produce timber for the local and/or export market will determine its selection of species, sizes and quality, and the level of financial capital required to purchase equipment and begin processing. This decision is again influenced by whether a community will apply for certification that verifies the sustainability of their operation.

Some non-government aid organisations find that the complex demands and substantial costs, coupled with uncertain rewards of certification, can make these operations hard to justify. International markets offer only a small premium for certified material (Australian importers have indicated that a price premium up to 5% could be offered for certified timber).

Forest certification is usually not required by local buyers, who are prepared to accept smaller volumes and lower grades of timber. Export markets, by contrast, demand large volumes of particular species at specific sizes and quality.

Export markets are difficult for communities because they need to select only well-known species that are free of defects, and meet precise specifications. Buyers accord more importance to the quality of the product than its certification credentials. Hence, it may not be commercially viable nor ecologically sustainable for a community to cut solely for the export market.

## Methods

### Background to the production and supply models

This analysis investigated the operation of a portable sawmill with supporting equipment (truck and tractor) so that community enterprises could avoid dependence on heavy manual labour to move the mill or transport sawn timber to roadside or market. While many communities and groups currently operate mills using manual labour, this was seen as a poor use of community members' time, and unsustainable physically and financially.

The portable mill processes four classes of timber boards that have market value or are a 'merchant grade' product: Class 1–A-grade timber; Class 1–B-grade timber; A-grade mixed hardwoods; and B-grade mixed hardwoods.

For the purpose of this study, an equal proportion (25%) of timber in each class is assumed to be produced unless stated otherwise. The volume of marketable timber that can be extracted from each tree varies in the range 35–50% of the log volume, depending on tree selection, how the log is felled and the effectiveness of milling.

### Alternative production and supply models

The following production and supply models were considered in the analysis. All models included costs associated with achieving and maintaining full forest certification over the 20-year analysis period, as well as the implementation of reduced impact logging practices for tropical forests.

The most viable production and supply models that communities can adopt to harvest their forest resource are considered to be as follows:

A. Communities working to achieve environmental certification process 'green' timber boards that are sold in the nearest commercial centre. The community is certified as Fair Trade, which is the first of three stages towards achieving full certification. No timber value-adding is undertaken.

B. Communities process 'green' timber boards where Category 1–A-grade material is sold to a central marketing unit, an organisation specifically established to export sawn timber material. All other timber is sold to local buyers. No value-adding occurs, and the community is certified as Fair Trade.

C. Communities value-add to their Category 1–A- and B-grade sawn timber via kiln drying and 'dressing'. The timber is then exported. All other timber (mixed hardwoods) is sold locally as 'green' material. The community is certified as Fair Trade.

D. Communities value-add to their Category 1–A- and B-grade sawn timber via kiln drying and 'dressing'. This and all other material (mixed hardwoods, green) is sold locally—no exporting takes place. The community is certified as Fair Trade.

### Financial model evaluation

A financial model was developed to evaluate the performance of these different production models over a 2-year time period.

The performance of each model was assessed using the following criteria:

1. profitability in each of the first 3 years of operation
2. average return on sales (or profits as a percentage of sales)
3. funds required to purchase the equipment and provide working finance
4. the pay-back period—the number of years it takes to repay the start-up investment from the free cash flow generated by the operation
5. i. the first 5 years of operation
   ii. over the 20 year period
5. net present value (NPV), which measures in present value terms the excess or shortfall of the stream of cash flows expected over the life of the operation. In calculating NPV, a discount rate of 20% is adopted to reflect the high risk of doing business in PNG, and the unstable regulatory and generally high inflation / high cost of capital environment. The annual headline inflation rate for the July–September quarter 2009 was 5.3%, compared with 13.5% in the same period of 2008. The Bank of Papua New Guinea maintains a tight monetary policy stance (the interbank lending rate is at 8%).

To understand how changing conditions affect the viability of a particular production and supply model, 'what-if' analysis was undertaken. In particular, what influence do changes in prices, productivity and a community's location and distance to its buyers have on the financial viability of its operation?

From surveys and interviews with various merchants and companies, it was established that timber sold to local buyers would attract the following prices (K (PNG kina))—overseas customers prefer appearance grade timbers (Class 1–A-grade) and this attracts a premium:

- Class 1–A-grade green sawn timber: sold locally, K1,000/m³; exported, K1,300/m³; dried and dressed, K2,000/m³ in local and export markets
- Class 1–B-grade green sawn timber: K650/m³; dried and dressed material K1,300/m³
- A-grade mixed hardwoods: K500/m³
- B-grade mixed hardwoods: K400/m³.

Local market conditions in PNG indicate that the same price is received for value-added timber that is sold locally or exported.

## Results

Analysis of the different production options (Table 1) found that the most profitable model was exporting higher value species as 'green' sawn timber via a central marketing unit, and selling all other timber

**Table 1.** Comparison of four different models based on harvesting and processing of 1,000 $m^3$ of log input and 50% recovery from forests located 100 km from the point of sale in Papua New Guinea

| Financial criteria | Model A | Model B | Model C | Model D |
|---|---|---|---|---|
| Total profits years 1–5 | K14,700 | K56,500 | –K507,000 | K69,600 |
| Total profits years 1–20 | K608,000 | K1,914,000 | –K3,183,000 | K429,000 |
| Average return on sales | 4.84% | 14.86% | –19% | 2.4% |
| Start-up investment | K780,000 | K780,000 | K1,800,000 | K1,800,000 |
| Pay-back time of initial investment | Year 4 | Year 3 | Not possible | Year 5 |
| NPV (20%) | Positive | Positive | Negative | Positive |

K = kina (PNG currency); NPV = net present value

locally (production option B above). This production model earned accumulated profits of K1.9m over the 20-year life of the study, achieved an average return on sales of 15% and had the shortest capital payback time (3 years).

The next most profitable model was the processing and sale of 'green' sawn timber for local buyers only (production option A). This achieved low profitability (accumulated profits of K0.6m over the 20-year life of the study) and a low return on sales (4.84%). Start-up capital costs were the same as the model involving the export of green timber (option B) but it took a year longer to pay back this capital.

Forest certification is a significant cost that is currently not expected in the local market. If communities choose not to pay for certification, the profitability of options A and B increases by 10% and 6% respectively.

The recovery of merchant-grade material from each log, and the distance to transport boards to buyers, have a large influence on profitability. Operations preferably need to achieve a minimum recovery rate of 42% and be within 140 km of their main buyers to achieve early and consistent profitability.

Investing in value-adding for the output from a single sawmill was not justified on current prices for timber. Both production models C and D are not attractive. Model C, exporting high-quality timber, resulted in substantial losses and it was not possible to repay the start-up capital. Model D, involving adding value and selling all material locally, achieved a low level of profitability (average return on sales of 2.4%).

Value-adding can double the sale price but is not justified for small-scale operations. To make value-adding profitable, a significantly higher scale of production is required to cover the high fixed and variable costs associated with operating a timber yard (4,000–5,000 $m^3$ log intake per year). However, higher levels of log harvest and production achieved through aggregation of smaller milling operations could make this model viable.

None of the models returned a profit in the first year of operating, while models A and B achieved profitability in years 2 and 3, and in nearly all subsequent years.

Distribution of profits may take different forms. Results indicate that profits can be paid back soon after commencement (years 3–5, subject to distance from market). However, communities may choose to make repayments to investors in smaller increments over a longer period of time to ensure that the operation has a comfortable level of working capital, and to make regular disbursements to the community.

## Discussion

In summary, this study has found that community-based small-scale portable sawmill operations can become economically viable. Profitability is driven by the following factors.

1. The entrepreneur and the team. The importance of leaders with good business development skills and willing workers cannot be underestimated. Successful operations need leadership that can manage the operation's affairs and effectively negotiate with buyers. Operations also require committed workers to work the mill at a high level of productivity. This will require attractive salaries and equitable distribution of surpluses to the community—to provide incentives for personal efforts, and to encourage those with the physical capacity, interest and willingness to learn through training and work on behalf of the community.
2. Market prices and operating costs. Timber prices fluctuate with general economic activity. In PNG this is substantially influenced by international mineral and agricultural commodity prices.

3. Mill productivity. The rate-limiting factor for a community forest enterprise is mill productivity. Maintaining maximum productivity from the capital investment is a critical determinant of profitability. Having a tractor to move the mill intact, push small logs, clear undergrowth and transport boards to a roadside can greatly increase production and profitability. A four-wheel-drive truck that can operate during the wet season can be used to transport timber to buyers. Operators have indicated that, with dedicated staff and mechanisation (tractor and skidder), production can reach 3 $m^3$ per sawmill per day.
4. Recovery. Profitability improves markedly with greater recovery of merchant-grade boards from logs. Careful selection and proper felling of logs can maximise the proportion of merchantable timber that can be extracted during the milling process.
5. Distance to market. Increased volume can offset distance. Producers located more than 400 km from a commercial centre can be marginally profitable if they produce at least 1,000 $m^3$ of boards per year. Private operators have indicated that to remain viable, they need to operate within 100 km of their buyers.
6. Capital. The way communities access capital to commence a portable sawmill operation is critical to its success. Taking on debt at high interest rates to purchase equipment has made it difficult for communities to operate and earn surpluses. In some cases, disillusioned communities stop production.

## Business models for portable sawmill operations

There appear to be only limited community-run portable sawmills in PNG that are profitable.

The likely reasons for these loss-making operations is that many communities and donors of portable sawmills do not have entrepreneurs with the requisite business-development skills to establish a viable business model that creates value for customers in a profitable way. Naively, some sections of the aid community involved in sustainable forestry seem to believe that providing communities with equipment, training and some working capital is sufficient to make a portable sawmill operation viable.

Organisations across the world, both large and small, have struggled and died because their business models have not matched the needs of their customers.

There are three dominant business models (Figure 1) used by the private sector to establish what an enterprise will and will not do. They are used to establish clarity as to how resources and activities create value for customers and the enterprise:

1. Product leadership—firms deliver leading-edge products. Their focus is on innovation, rapid product development and marketing. Product leaders continually 'reinvent' their business.
2. Operational excellence—firms deliver lowest total cost through a combination of quality, price and ease of purchase that competitors cannot match. Their focus is on superb execution and cost control.

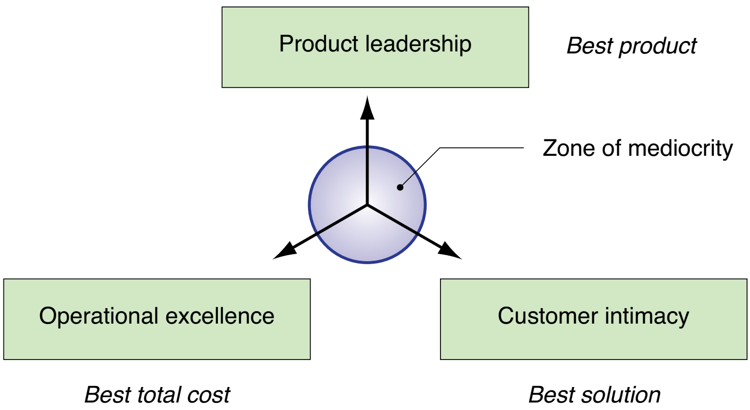


**Figure 1.** The dominant business models used by the private sector

3. Customer intimacy—firms have close relationships with carefully selected customers. Their focus is on providing extensive customer support and on cultivating the lifetime value of their customers.

Good strategy involves choosing one of these three business models to excel in, and providing fit-for-purpose performance in the other two. Organisations that attempt to excel in more than one of these strategic themes usually end up in trouble.

The customer intimacy model is most appropriate for community-based portable sawmill operations. Communities adopting this model strive to deliver excellent service to a small number of customers.

Some non-government aid organisations such as the Foundation for People and Community Development argue that communities need to increase production and achieve scale if they are to end the current outcomes of subsidised loss-making operations. Perhaps unbeknown to them, they are proposing the operational excellence model, a cost–leadership approach based on achieving a high volume of output. This model is adopted by most large forest and wood products companies.

Most communities do not have sufficient forest resources, skills and access to financial capital to pursue the more complex operational excellence model. Moreover, this model would see communities competing on price, quality and product range against large, established companies. This approach is not recommended for community forest enterprises in PNG.

# Conclusion

Community-based portable sawmill operations that are harvesting and processing 1,000 $m^3$ of log input annually can be profitable. At this level of production, the milling of ‘green’ boards is sufficient, and any attempts to value-add will result in financial losses.

It is our assessment that community-run sawmill operations need to establish a point of difference compared with the large forestry companies by executing the customer intimacy business model well. This is the dominant model used by small enterprises, particularly where they have little capacity to distinguish their product (as in the case of wood products).

The path to economic sustainability for community sawmill operations in PNG is to:

1. establish the customer intimacy business model within communities through entrepreneurs
2. devise a simple operating and financial plan and use it to guide and assess progress
3. prepare a more detailed financial model for investors, providing the minimum level of funding required, expected payback to investors, key financial ratios etc.

Enterprises that do not have clarity as to their target market, and how they will operate to create value for their customers and the enterprise, are doomed to fail. It appears that many community forest operations in PNG have placed their business at risk by not commencing with a cogent business model and financial plan to focus their activities in a profitable way on a select group of customers. Entrepreneurs are needed to adopt a business model that fits with their resources and capabilities.

# A simple planning system for sustainable timber harvesting in Papua New Guinea

**Rodney J. Keenan[1], Cris L. Brack[2], Martin Golman[3] and Jerome K. Vanclay[4]**

*Abstract*

Planning and management of forest resources in Papua New Guinea (PNG) has sometimes resulted in overcutting, resource depletion, unintended environmental impacts and uncertainty about the long-term capacity of forests to supply the future needs of local communities or industry. Sound inventory and planning are critical for sustainable forest management. Good systems are in place in PNG to determine forest area, forest inventory and future forest growth. However, they have not been integrated effectively for strategic forest planning. This paper describes some simple tools for integrating this information to provide more robust estimates of future timber yields and more realistic levels of annual allowable cut. It allows for assumptions relating to available forest area and harvest intensity to be explicitly presented and assessed by those approving forest operations. The system is scalable and could be applied to smaller areas under community management, larger timber-harvesting operations or national-level analysis. The operation of the system is demonstrated through application to a case study area in Madang province. Some of the challenges, constraints and desired improvements to the system are discussed. Forest planning is not a linear or static exercise. Plans for long projects covering large areas must be periodically reviewed to incorporate new information, changing standards and changing community expectations.

## Introduction

The forests of Papua New Guinea (PNG) are among the world's most complex natural resource management challenges. With 33 million hectares of tropical forest, PNG has the third-largest expanse of tropical forests in the world. These forests are complex in composition, structure and function. PNG society is also complex. The population of 5 million has over 800 language groups and a wide diversity of social and land-ownership arrangements. Almost all forests are under customary ownership by local clans or individuals. Forests are of major importance for the livelihoods of rural communities, providing construction materials, food, medicines, clean water and other non-timber products to local communities, They are sometimes also used on a rotational basis for gardening. Forests are often the only source of cash income for many communities for education and health services. For the global community, PNG forests have significant value for conservation of tropical forest biodiversity and carbon storage.

Planning and management of forest resources has sometimes resulted in overcutting, resource depletion, unintended environmental impacts and uncertainty about the long-term capacity of forests to supply the future needs of local communities or industry. Development and use of forest resources is seen by most sectors of the community as an integral

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component of national development, but accommodating diverse community interests in planning forest development is a significant challenge.

This paper provides an overview of forest-management planning, presents information on the planning and inventory systems in PNG, and describes the development and application of a simple harvest-planning tool that can enable better decision-making in setting allowable cuts for timber harvesting from forests in PNG. It was developed as part of a project that aimed to build capacity and knowledge within PNG for forest inventory, and planning and analysis of alternative options for timber harvesting. The project focused on improving capacity for strategic-level planning, particularly for inventory, assessment and predicting the supply of timber resources.

## Forest-management planning

Forest-management planning involves:

- setting objectives for the forest-management unit
- specifying management actions (e.g. harvesting, regeneration, fire control) to be undertaken in the forest to meet those objectives
- implementing actions
- reviewing outcomes and revising plans.

Objectives for strategic plans are generally developed by forest owners and managers in consultation with those in the community who will be affected by the activities.

Planning is considered an essential component of sustainable forest management. Plans demonstrate that forest managers have taken into account the full range of forest uses, products and values in determining the management of forest resources. Ideally, strategic plans should be reviewed regularly (every 5 years) to ensure that they continue to reflect community requirements and new information.

Management to produce a sustained yield of products or services can be achieved in a number of ways. Historical concepts of sustained yield from forests have generally been based on production of timber from even-aged forest stands in an estate with a balanced set of age classes, such as might be established in developing a forest plantation area.

Natural tropical forests are usually managed on a selection system. In this case the goal is to maintain a balance of tree age and size classes across the area under management. In a forest that has had no previous harvesting, there is usually a high proportion of trees of larger size classes.

In these types of forests, the first cutting cycle will generally result in higher levels of production than that which can be achieved under ongoing management of the remaining forest. This cut is also based on a forest with a high proportion of larger trees, and will produce a very different kind of resource in terms of log size to that from second and subsequent harvests, which will be based on smaller regrowth trees. A policy or management decision is therefore often required to determine the length of time over which this first cut will occur. This will be determined by the market and the desires of the forest owners.

## PNG forest policy and planning

The 1991 PNG National Forest Policy was prepared to remedy the shortcomings of the previous 1979 policy and to accommodate the recommendations of the Barnett Forest Industry Inquiry (1987). The policy was endorsed in 1990 by the National Executive and was followed by a new Forestry Act being passed by Parliament in 1991.

The policy sets out objectives for the management and protection of the nation's forest resources as a renewable natural asset, and to utilise them to achieve economic growth, employment creation, greater PNG participation in industry and increased viable onshore processing. Forests are to be identified and classified as production, protection, reserve or salvage forests, or land suitable for afforestation under the policy.

PNG has detailed legislation covering forest planning and management in the Forestry Act 1991 and amendments in 1993. Later amendments in 1996 mainly related to changes in the composition and selection of the Board. In addition, harvesting operations are covered under the Key Standards for Selection Logging in Papua New Guinea and the Papua New Guinea Logging Code of Practice (1996).

The National Forest Policy and planning arrangements in PNG are largely directed at providing the policy and regulatory framework for producing timber rather than providing for the full suite of products, values and services encompassed by sustainable forest management (Hammond 1997). However, in establishing an appropriate level of timber supply, the forest planning process needs to take account of these other values. Historically, resource-level information has been used to schedule the production of timber. Recently, forest-management systems have been devised to consider an appropriate balance between competing values (Ferguson 1996).

Natural forests in PNG have high species diversity, and only a relatively small proportion of species has timber properties suited for wood products. Silvicultural prescriptions are relatively rudimentary, and timber-harvesting operations are based on selective harvesting with a simple size limit restriction of 50 cm diameter at breast height (DBH).

Sustained yield management is set out as the guiding principle for forests classified as production forest. The National Forest Policy states that:

> The National Forest Plan shall designate the potential of each province and be based on a National Forest Inventory of commercial forest resources complied and updated on a province by province basis. …The allowable cut will be set initially by dividing the total merchantable resource within the production forest by an assumed cutting cycle of 40 years.

The plan sets out fairly general strategies for inventories designed to estimate the volume and quality of the forest resources. The policy sets an ambitious target—to undertake a rapid resource appraisal within 1 year, as described by Hammermaster and Saunders (1995).

Other requirements for forest planning and inventory in PNG are specified in the Forestry Act and in planning, monitoring and control procedures. For large areas such as Forest Management Areas (FMAs) in PNG, plans are generally developed at three levels: strategic (20–40 years), tactical (5–10 years) and operational (1 year) (Figure 1).

A major problem with setting the annual allowable cut (AAC) for FMAs has been that operations that are intended to last for 35–40 years (and then provide for a future harvest at a similar level) have often only lasted 10–15 years.

Some of the reasons for this emerged during a review of planning and inventory, where the following issues were raised by government and research participants:

- The National Forest Policy states that all agreements and permits will be conditional upon broad land-use plans, but there is currently no comprehensive land-use planning process in place in PNG.
- Road access is a major factor in resource planning. Roads serve different functions besides timber extraction; for example, for agriculture and other access to towns and villages. At present there is no general infrastructure plan within which access for timber harvesting can be considered.
- Inventory requirements for tactical and operational planning are too demanding. The industry operator can decide what is required for operational purposes.
- Estimation of the available area is based on simplistic assumptions that do not adequately take into account accessibility, protection of watershed values, slope restrictions, conservation or community values (Table 1).
- There is no process for review of the AAC during the life of a project to take into account the rate of harvesting or new information on the FMA.

The 'net harvestable area' can be difficult to estimate in the context of selection harvesting systems and uneven aged stands, and has been the cause of major discrepancies between predicted and realised harvest volumes in Australia and other places (FAO 1998; Whiteley 1999).

Determining the precise boundary of the net harvestable area may be difficult, especially in broken terrain where harvesting is limited by slope in an irregular way, or where the quality of forest is marginal and only selected areas or patches are suitable for harvesting. By definition, the net harvestable area is the area remaining after eliminating various exclusion areas. Exclusions relate to the following:

- riparian strips, corridors and other units set aside from harvesting for whatever reason (environmental, cultural or scientific purposes)


**Figure 1.** Forest planning requirements under the Forestry Act 1991

**Table 1.** Reasons why native-forest timber resources are cut much sooner than planned—results from discussions at a workshop in Papua New Guinea, May 2003

| AVAILABLE FOREST AREA OVERESTIMATED |
| --- |
| • Overestimating the total forest area (i.e. mapped forest areas that have been converted to other land cover)<br>• Accessibility not adequately determined (e.g. effects of steep slopes, difficult soils, inundation)<br>• Roading access not known at inventory—may reduce areas that are economic to road access due to low volumes and/or high roading costs<br>• Conservation requirements not adequately met<br>• Impact of Code of Logging Practice not adequately addressed (e.g. stream buffers, slope or other restrictions)<br>• Village cultural/gardening requirements need to be quantitatively evaluated<br>• Landowner intentions may be unclear or change<br>• Excessive snigging distance may reduce area availability due to uneconomic haulage |
| AVAILABLE TIMBER VOLUME PER HECTARE OVERESTIMATED |
| • Inventory design may be inadequate or biased<br>• Inventory may be out of date or not current<br>• Timber quality may have been degraded through fire, disease or other disturbance (e.g. 1997 drought and fires)<br>• Inventory used different log standards to those applied by industry (e.g. 50 cm DBH limit used for inventory but some companies harvest only above 60 cm)<br>• Industry uses a more limited number of species to those assessed<br>• Industry uses different standards for log length or defects to those in the inventory<br>• Potential bias in tree volume equations |

- areas deemed too steep to harvest using prevailing systems
- larger patches of forest containing insufficient timber to support a harvesting operation for the target products.

The physical area of disturbance in a selection harvesting system comprises the immediate area of trees damaged by felling single trees or small groups of trees (typically 3–20 trees per hectare in PNG), and associated snig tracks, roads and loading areas. Patches of disturbance are separated by small areas of more-or-less undisturbed forest, often containing trees less than the merchantable size limit for harvesting plus both large and small non-commercial trees. This mosaic of disturbed and undisturbed forest together defines the net harvestable area.

In the context of broad-scale inventory (as required at the FMA scale), it is neither practical nor efficient to prepare detailed net area maps for a surveyed area. What is required is that the sampling system used to collect volume information also provides an independent estimate of the netting factor that should be applied to the gross area sampled to allow realistic estimates of both loggable area and volume to be generated.

Analysis of available area using alternatives to the simple assumptions being applied in PNG indicated that these could reduce the area of forest available for harvesting by more than 50% (Table 2), with increased reductions in area available during second and subsequent harvests.

The fundamental requirements for a production forest-management planning system include:

1. a statement of the area of forest in different age, forest type and/or productivity classes, accessibility criteria, riparian zone, priority protection, community use and other constraints on timber production
2. an inventory of forest timber and other values
3. a growth model to estimate the projected yield of timber volume or mass over time; for uneven-aged forests, this model should reflect the effect on forest growth of different intensities of harvesting
4. a system for integrating forest area, inventory and growth modelling, and projecting the effects of different harvesting regimes on forest composition and structure.

## Planning system and yield calculation

Harvest levels can be set using area or volume control. In its simplest form, area control divides the forest area by the cutting cycle to determine an area to be harvested each year. Volume control determines the harvest volume based on an estimate of the current timber volume, stand increment following harvesting, and desired production to meet industry or community needs. Currently, PNG harvest planning is based on volume control; that is, an annual allowable cut is set based on the strategic inventory.

It has been argued that planning should shift to area control, with industry permitted to cut only a given area of forest each year. Chatterton et al. (2000) suggested that, instead of the Papua New Guinea Forest Authority (PNGFA) committing to an AAC statement in the tender call, it provide a commitment that the final net area agreed for harvesting will be made available under the terms of the Papua New Guinea Logging Code of Practice (1996), as amended from time to time. The project would be divided into a number of coupes depending on the size of the overall project; irrespective of the volume, a successful tenderer would be restricted to operating no more than 6/40 of the gross area in any 5-year period.

These different types of planning and control methods have advantages and disadvantages (Table 3). The most effective approach to meet the needs of industry and ensure that harvesting lasts the intended cycle is to use volume control and review the annual cut periodically (e.g. every 5 years), based on records of the volume removed and the area harvested. These volumes per hectare can be used to recalculate the remaining volume in the project area. This is divided by the number of years remaining in the cycle to set a new allowable cut level.

**Table 2.** Reductions in area available for harvesting associated with different factors based on analysis of land tenure, topographic maps, data from the Forest Information and Management System—example is for the middle Ramu Forest Management Area in Madang province, Papua New Guinea

| | Area (ha) | Percentage |
|---|---|---|
| Gross forest area | 156,600 | |
| Exclusions from 1st cycle | | |
| • Conservation reserve | 31,570 | 20.2 |
| • Slope outside conservation | 14,490 | 9.3 |
| • Altitude outside conservation | | |
| • Inundation outside conservation | | |
| • Fragile | 3,598 | 2.3 |
| • Streamline buffers not in above | 17,135 | 10.9 |
| • Community reserves not in above | 5,875 | 3.8 |
| • Other inaccessible | 259 | 0.2 |
| 1st cycle net area | 83,673 | 53.4 |
| Additional exclusions after 1st cycle | | |
| • Conversion to gardens | 10,400 | 12.4 |
| • Regrowth area reduction | 4,184 | 5.0 |
| • Roading | 4,184 | 5.0 |
| • Other | 3,887 | 4.7 |
| 2nd and 3rd cycles net area | 61,018 | 39.0 |

**Table 3.** Advantages and disadvantages of area versus volume control of timber harvesting in a variable native forest—results from a workshop held in Papua New Guinea, May 2003

| | Area control | Volume control |
|---|---|---|
| Advantages | • Harvesting lasts full cycle<br>• Accurate inventory less important | • Consistent annual cut (while this lasts)<br>• Allows for industry requirements in species and size classes |
| Disadvantages | • Highly variable annual harvest<br>• Industry must accept species in the area | • Cut may not last full cycle<br>• Depends on accurate inventory estimates |

# Methodology

## A simple spreadsheet harvest-planning tool

The project developed a simple spreadsheet planning system to provide a sound basis for forest-harvest planning by volume control. The tool facilitated the integration of forest area, inventory and growth information to calculate timber yields under different management scenarios. The tool was developed using Microsoft® Excel software. It provides a simple system for integrating data and a basis for analysis of alternative cutting strategies.

The input and output pages of the tool are shown in Figures 2 and 3. The user enters data on forest inventory, growth and yield (Figure 2). These are divided into nine different species quality groups and size classes so that the allowable cut can also be separated into these different categories. The user indicates the preharvest data, ingrowth, upgrowth (those trees moving from one size class to the next) and proportion of volume lost each year due to mortality and harvesting damage.

Area information for a forest-management unit is input by the user (Figure 3). The main factors that reduce available forest area (conservation reserves, altitude, inundation, fragile soils) are those contained in the Forest Management and Information System. Provision can also be made for stream buffers and community reserves. This 'discounting' of the gross forest area needs be done in a systematic way so that double counting does not occur.

Estimation of the area available for cutting in second and subsequent cycles needs to consider additional factors such as the area permanently lost to roads, to gardens or other agriculture that enters the regrowth/fallow cycle, and to impacts of landings and skid tracks. These estimates are entered as percentages.

The system assumes a standard volume per hectare across the area for which timber production is considered. Once area and volume data are entered, the user can enter a cutting cycle length in years (Figure 2), and a proportion of each minimum export price (MEP) code and size class that will be harvested in each cycle.

The system then calculates the annual yield based on the harvesting strategy and the available area (Figure 3). This can be used to set the level of the allowable cut. The user can also enter a value figure and a discount rate, and the system provides an assessment of net present value.

Output from this system can be used to assess the implications of alternative management options. For example, a heavy cut of all trees greater than 50 cm DBH (similar to current log-export operations) will result in a high yield (170,000 $m^3$/year) in the first cutting cycle of 35 years, but a dramatic decline in second and third cycles to less than 50,000 $m^3$/year (Figure 4a). If the cut is restricted to trees in MEP codes 1, 2, 3 and 6, and trees greater than 65 cm DBH (specifications used by some local processors), yield will decline to 130,000 $m^3$/year in the first cycle and to about 20,000 $m^3$/year in the second and subsequent cycles (Figure 4b).

Adopting a management regime that leaves a proportion of currently commercial trees (particularly those of 50–65 cm DBH) for future cycles can result in a longer term, uniform flow of wood of about 50,000 $m^3$/year (Figure 4c).

# Discussion

Large-scale timber-harvesting operations of native forest in PNG have generally not been managed in a way that maintains an ongoing flow of timber and other benefits to the local landowner groups. While the specified cutting cycle of 35–40 years is intended to provide the basis for a continuing forest operation in areas under FMAs, this has not generally been the case, with the harvest levels set for most operations leading to the depletion of the merchantable forest within 10–20 years. This is due to overestimation of the available forest area and the merchantable volume, and flawed assumptions in the calculation of the allowable cut.

The simple harvest-planning system presented here provides an improved basis for estimating the yield associated with different types of harvesting operations, and for establishing the annual allowable cut. It allows for assumptions relating to available forest area and harvest intensity to be explicitly presented and assessed by those approving forest operations. The system is scalable and could be applied to smaller areas under community management, larger operations or even a national-level analysis.

A key challenge in implementing the system is having robust information on the following:

- standing volume based on an unbiased systematic or random sample of the forest area under consideration (see Brack 2011)
- information on recruitment and forest growth after harvesting
- the impacts of harvesting and other factors on stand mortality

- the current forest area and the extent of area that might be unavailable due to slope, access, conservation reserve, village use or other constraints
- the extent of future impacts such as fire, gardening and conversion to agriculture.

These will vary considerably with the region, location, topography and size of the harvesting area, and with accessibility factors such as proximity to all-weather roads.

As indicated earlier, for a native forest area that has not previously been subject to harvest, the level of the initial cut and the period over which it occurs is a management decision. It will be determined by factors such as the minimum level of harvest to justify the development of infrastructure such as roads or ports, and the resource required to support the establishment of a processing facility. A 'non-declining, even flow' of timber (e.g. Figure 4c) is often seen as the most desirable goal of management for timber harvest. However, this does not have to be the case, and alternative options resulting in a 'fall-down' to a longer term sustained yield based on harvesting of

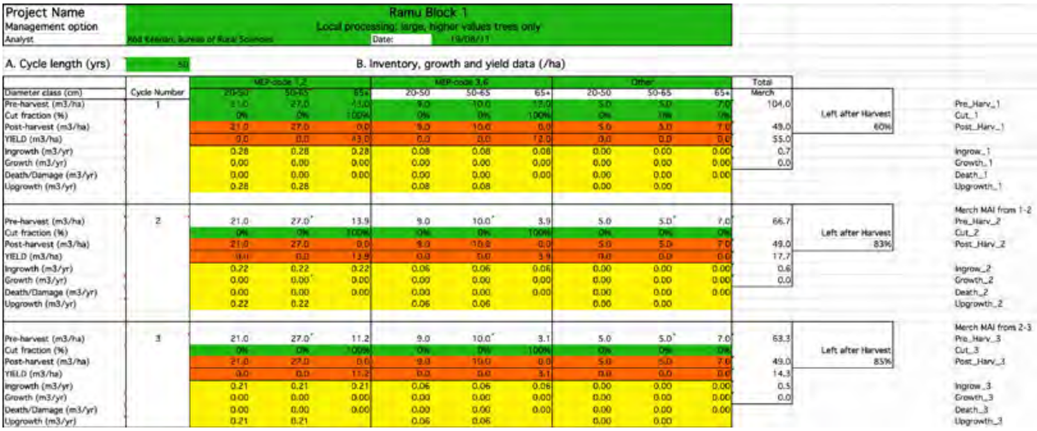


**Figure 2.** Simple harvest planning tool developed using Microsoft® Excel software—section showing the timber inventory by size class and tree species quality (MEP code). User defines the cut fraction in each class and provides estimates of growth, mortality or damage. Data are for the middle Ramu Forest Management Area in Madang province.

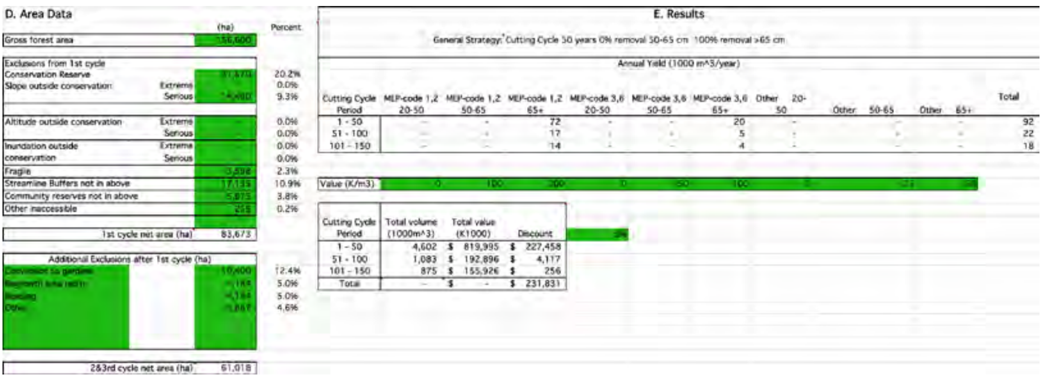


**Figure 3.** Simple harvest planning tool using Microsoft® Excel software—section showing the planning unit area data, area exclusions in first and subsequent cutting cycles, timber yield and total volume, and value information. Data are for the middle Ramu Forest Management Area in Madang province.

regrowth forest may be a legitimate and sustainable forest-management approach, provided that other values (e.g. water, biodiversity, cultural or subsistence benefits) are properly provided for.

The system could be improved by linking it to a growth model that projects stand structure from current inventory, based on growth functions determined from sound data on forest growth. This could also be used to provide information on likely stand structure (tree size distribution and composition remaining after harvesting), and could be compared with post-harvest inventory data. If these data were available, the system would be updated and re-run on a regular basis in order to review the allowable cut based on harvest yield information and assessment of future available volume.

# Conclusions

Planning and management of forest resources in PNG have sometimes resulted in overcutting, resource depletion, unintended environmental impacts and uncertainty about the long-term capacity of forests to supply the future needs of local communities or industry.

Sound inventory and planning are critical for sustainable forest management. Good systems are in place in PNG to determine forest area, forest inventory and future forest growth. However, they have not been integrated effectively for strategic forest planning. Area and inventory systems need to be regularly updated to reflect harvesting and other disturbances, changes to policies and codes of practice, and changing industry log standards. More inventory

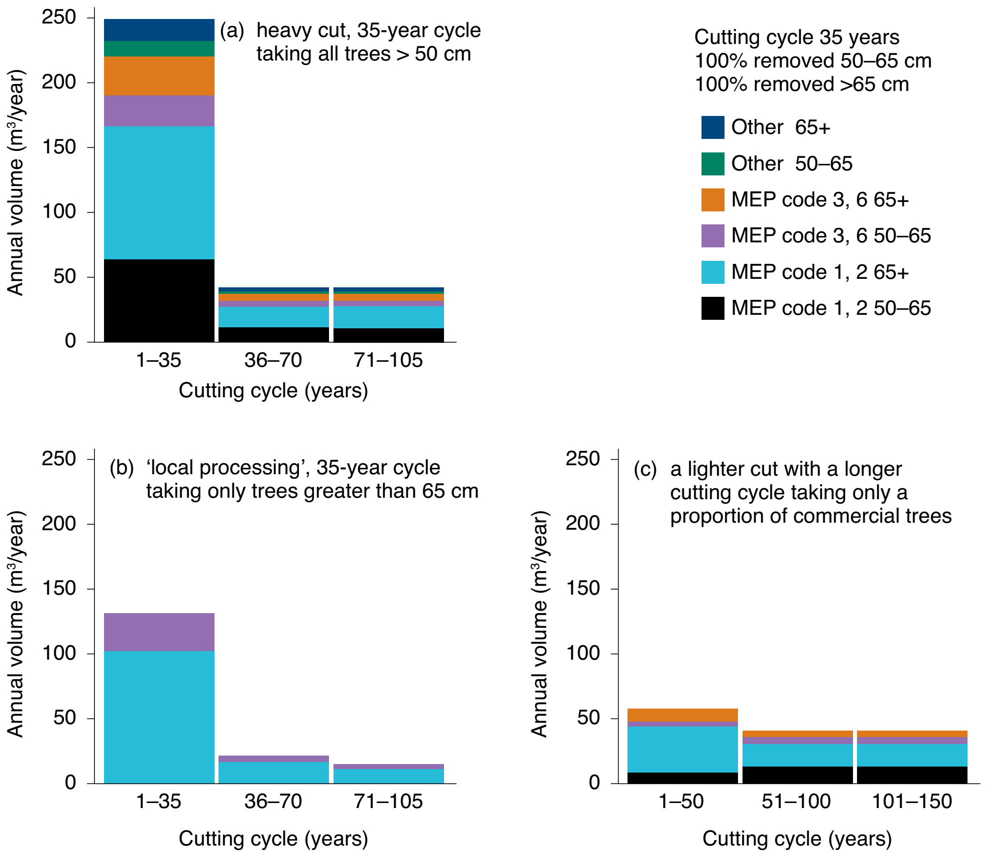


**Figure 4.** Management simulations using the simple harvest planning tool for the middle Ramu Forest Management Area in Madang province, Papua New Guinea. Estimated available forest area in each case is 84,000 ha. MEP codes 1 and 2 are higher quality timber species, MEP codes 3 and 6 are lower quality species, and 'other' is other merchantable species.

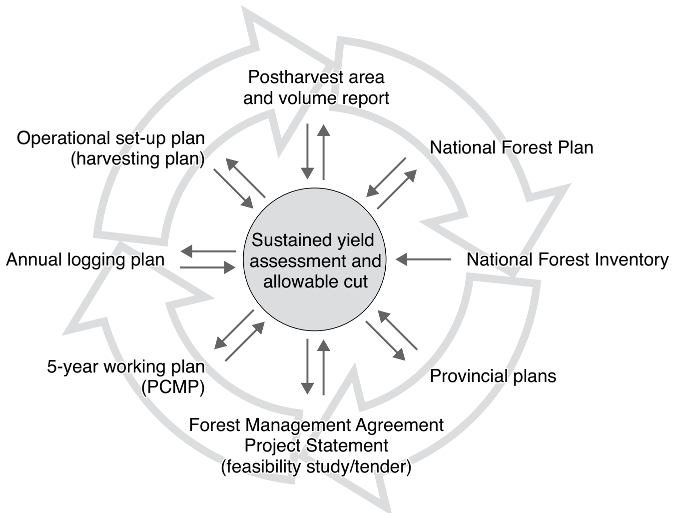


**Figure 5.** An 'adaptive management' model for forest planning in Papua New Guinea that links forest assessment and planning at different scales

effort should be put into postharvest assessment. This will provide more-valuable information for strategic planning and future management. Permanent sample plots need to be maintained and remeasured to provide sound information on the growth of cutover forests.

Application of simple calculation tools can ensure that forest inventory, growth and area information are effectively integrated to provide more robust estimates of future timber yields in order to set more realistic levels of annual allowable cut.

Forest planning is not a linear or static exercise. Plans for long projects covering large areas must be periodically reviewed to incorporate new information, changing standards and changing community expectations (Figure 5).

## Acknowledgments

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# Evaluating scenarios for community-based management of cutover forests in Papua New Guinea

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*Abstract*

There is an increasing demand for multiple objectives from forest management worldwide, particularly for tropical forests. Tropical forest management is challenging because of structural complexity, diverse composition and a wide range of stakeholder expectations and requirements. Uncertainties in tropical forest management also make sustainable forest management in the region a major challenge for governments, non-government organisations, local communities and the timber industry; hence, traditional methods such as straightforward projections may not be able to meet these challenges. Therefore, new management approaches, creative processes and policy directions are required (e.g. policies relating to community forestry) to meet these challenges.

For the past 20 years, much of the focus of formal forest management and forest policy in Papua New Guinea (PNG) has been on large-scale conventional harvesting to meet national requirements for economic development, with little attention given to community-level forest management. However, forest management by local community groups, particularly with the use of portable sawmills throughout PNG, has increased dramatically in recent years.

Evaluating scenarios for previously harvested forests in PNG is a new approach to tropical forest management. This study aims to develop scenario analysis and evaluation tools for assisting decision-making in community-based forest management in PNG.

The methodology used in this study is a combination of qualitative analysis of local people's interests and expectations in small-scale timber harvesting, and quantitative analysis of forest resources, costs and income associated with different management scenarios at two case study sites in PNG. A scenario analysis and evaluation tool called a decision-tree model for community-based forest management in PNG has been developed and presented as part of the outputs from this study. A new policy direction relating to community forestry is therefore necessary in order to adopt the systems developed in this study in the future management and utilisation of previously harvested forests at the community level in PNG.

## Introduction

In Papua New Guinea (PNG) there are many problems associated with forest management. For example, apart from stakeholder demands, land and forest ownership is complicated and there is also political interference and corruption in the forestry sector. At present, the production capacity of cutover forest areas and secondary forests in PNG is not well understood, and the future of marketing wood products from native forests is also uncertain because most overseas buyers are targeting timber and wood products from forests that have been managed in a sustainable way. Accessible primary forests are being exhausted in PNG through commercial timber harvesting and other land uses such as large-scale forest conversion to agriculture and

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shifting cultivation; therefore, future forest management will begin to focus on cutover secondary forests. Given customary ownership arrangements, the future management of these forests is likely to be decided by local community groups. A major challenge is the development of ecologically, socially and economically sustainable management systems for cutover forests that meet the needs of community forest owners.

Throughout tropical countries, communities have raised concern that very few benefits have been reaching the owners of land and forests after large-scale commercial harvesting. Furthermore, local people value forests not only for timber products but also other benefits and services; hence, there has been increasing involvement of local community groups in small-scale forestry projects. Many of these projects are community based and have involved small-scale sawmilling with the primary aim of producing sawn timber to build a home and community facilities such as schools, and to sell surplus sawn timbers to generate some income to improve livelihoods.

In PNG, non-government organisations (NGOs), community-based organisations and international conservation groups have participated in community forestry activities, including the Village Development Trust (VDT), Eco-forestry Forum, World Wide Fund for Nature, Foundation for People and Community Development (FPCD), and Madang Forest Resource Owners Association (FORCERT 2010). Certification of forest management is seen as a requirement for the forestry sector in the tropics (Alder et al. 2002) as it has the potential to promote sustainable forest management in the region, and increase incomes for communities. Forest certification has developed as a way of providing timber consumers with information about the management of forests from which certain timber products have originated. Regardless of efforts to promote Forest Stewardship Council (FSC) certification in PNG, most community groups have very little capacity to achieve FSC standards. They find that meeting certification requirements is quite difficult and the costs of becoming certified are high (Scheyvens 2009; FORCERT 2010).

Evaluating scenarios is a new approach to tropical forest management in PNG. Use of scenarios can provide a tool for planning creatively for the future (McDonald et al. 2005). Because of the complexity of tropical forest, compounded by complicated land and forest resource ownership, the scenario method is considered an appropriate approach for adaptive management of cutover forest by communities in PNG. The method involves the participation of stakeholders in forest management, and is applicable when there is a need to explore possibilities. Scenario-based techniques are tools for improving anticipatory rather than retrospective learning (Wollenberg et al. 2000)—they may assist forest managers to make decisions based on an anticipated range of changes. Elements of the scenario approach suitable for community-based forest management are based on appropriate participatory rapid appraisal techniques.

The objectives of this paper are to develop scenario analysis and evaluation tools for assisting decision-making in community-based forest management through a participatory action research (PAR) protocol with the participation of two local community groups in PNG.

## Methodology

This study involved a combination of qualitative analysis of local people's interests and expectations in small-scale harvesting, and quantitative analysis of forest resources, costs and income associated with different forest-management scenarios at two case study sites in PNG.

### Qualitative data collection and analysis

The qualitative component of this study involved a standard PAR protocol (Maguire 1987; Stringer 1999) that included field visits, meetings and interviews with stakeholders in the pilot region. Fieldwork involved extensive consultation with local communities (Yalu and Gabensis villages), government agencies (Papua New Guinea Forest Authority; Papua New Guinea Forest Research Institute), timber industries (LBC, Madang Timbers, Santi Timbers) and NGOs (VDT, FORCERT, FPCD, central marketing units (CMUs)) in the pilot region.

Two case study sites were selected in a region where extensive timber harvesting has taken place in the past (Figure 1). Fieldwork involved field visits and meetings to explain the purpose of the research to the communities. The actual interviews were conducted in four parts in order to understand the current uses of forest by communities and how they would like to manage their forests in the future. Scenario development involved the participation of communities at the two sites in village meetings to gauge their views, and in field interviews to assess their interests and expectations on how they would like to manage their forests in the future.

## Field interviews

Eleven individual structured interviews (eight in Yalu village and three in Gabensis village) were conducted with two community groups (Figure 2). These groups are not representative of the region; rather, they were chosen based on their involvement in previous small-scale timber harvesting, and they are located in a region subject to extensive harvesting of primary forests in the past, leaving behind mostly cutover forests.

Despite the sample in this research not being representative of the region due to the small sample size, we considered that the main aim of the interviews was to understand community attitudes towards small-scale timber harvesting, a prerequisite to developing forest-management scenarios. The individuals interviewed are members of the two community groups who have been involved in small-scale timber harvesting for the past 10 years, but with very little capacity to expand their operations. The outcome of the interviews provided some background on how communities would like to manage their forests in the future. The data for field interviews were analysed using both the qualitative data analysis software NVIVO (current and future uses of forest, community attitudes towards small-scale timber harvesting) and the quantitative software SPSS and Minitab (used for analysis of scenario indicators and for a chi-square test).

## Scenario development

Scenarios for community-based forest management were developed from local communities' participation in this study. The analysis of local people's current and future uses of forests, and their preferences on how they would like to manage their forests in the future, were the key component of the field interviews and formed the basis of scenario development. Their preferences were analysed as scenario indicators, which were then used to develop the scenarios. The whole process, from field interviews through the PAR approach to analysis of local people's preferences for future forest management, resulted in the development of the following major scenarios:

1. community sawmill
2. local processing
3. medium-scale log export
4. carbon trade.

The analysis of scenario indicators used a chi-square test to determine whether there was an association between the different forest-management

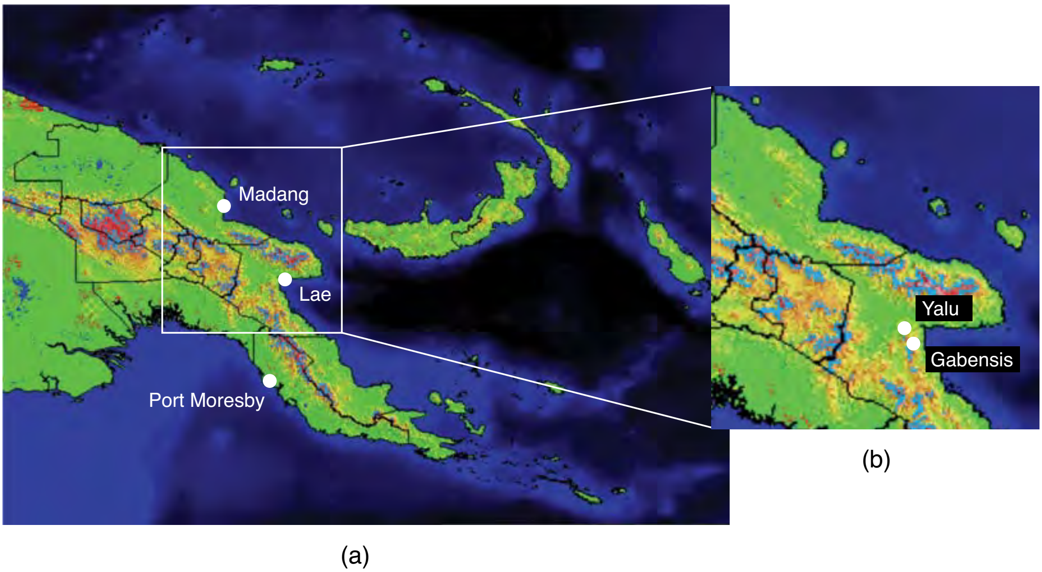



**Figure 1.** Map of case study sites selected for the study: (a) region in Papua New Guinea where extensive harvesting has taken place in the past, and (b) approximate location of the two communities (Yalu and Gabensis villages) in Morobe province, where the study sites are located

options (scenarios) and the preference levels of the individuals interviewed (Table 1; Figure 6). For the purpose of this paper, only the local processing scenario was tested, using a decision analysis model developed in this study.

## Quantitative data collection and analysis

The quantitative component involved assessment and analysis of forest resources at the two case study sites. The resources were assessed using a stratified random point-sampling technique to estimate the residual timber volume and above-ground forest carbon in the two community forest areas (see Fox et al. (2011) for the methodology).

Data relating to small-scale harvesting were also collected, including costs of labour, equipment, transport, marketing and certification; sawn timber prices; and exported timber volumes and prices. For the different forest-management scenarios, the associated costs and income were analysed and fed into a decision analysis model developed in this study (Figure 3). The scenario outcomes from this system were further evaluated to determine which scenario returned the highest expected monetary value (EMV). Based on this type of analysis, a forest manager can make an informed decision as to which scenario best suits the future management of a particular community forest area.

(a) (b) (c)

**Figure 2.** Field visits, meetings and interviews at the two case study sites: (a) author interviewing a participant at Gabensis village, (b) author interviewing a participant at Yalu village, and (c) a female participant raising a point during a meeting at Yalu village

## The decision-tree model

A scenario analysis and evaluation tool called the decision-tree model (Figure 3) has been developed for community-based forest management. The model is based on spreadsheet modelling and a decision-analysis technique. The decision tree comprises such concepts as decision (square) nodes, decision branches, event (circle) nodes, event branches, terminal nodes (end of a branch), terminal values, allocation of probabilities along the event (chance) branches when there is an uncertainty, cash flows along the branches, and a

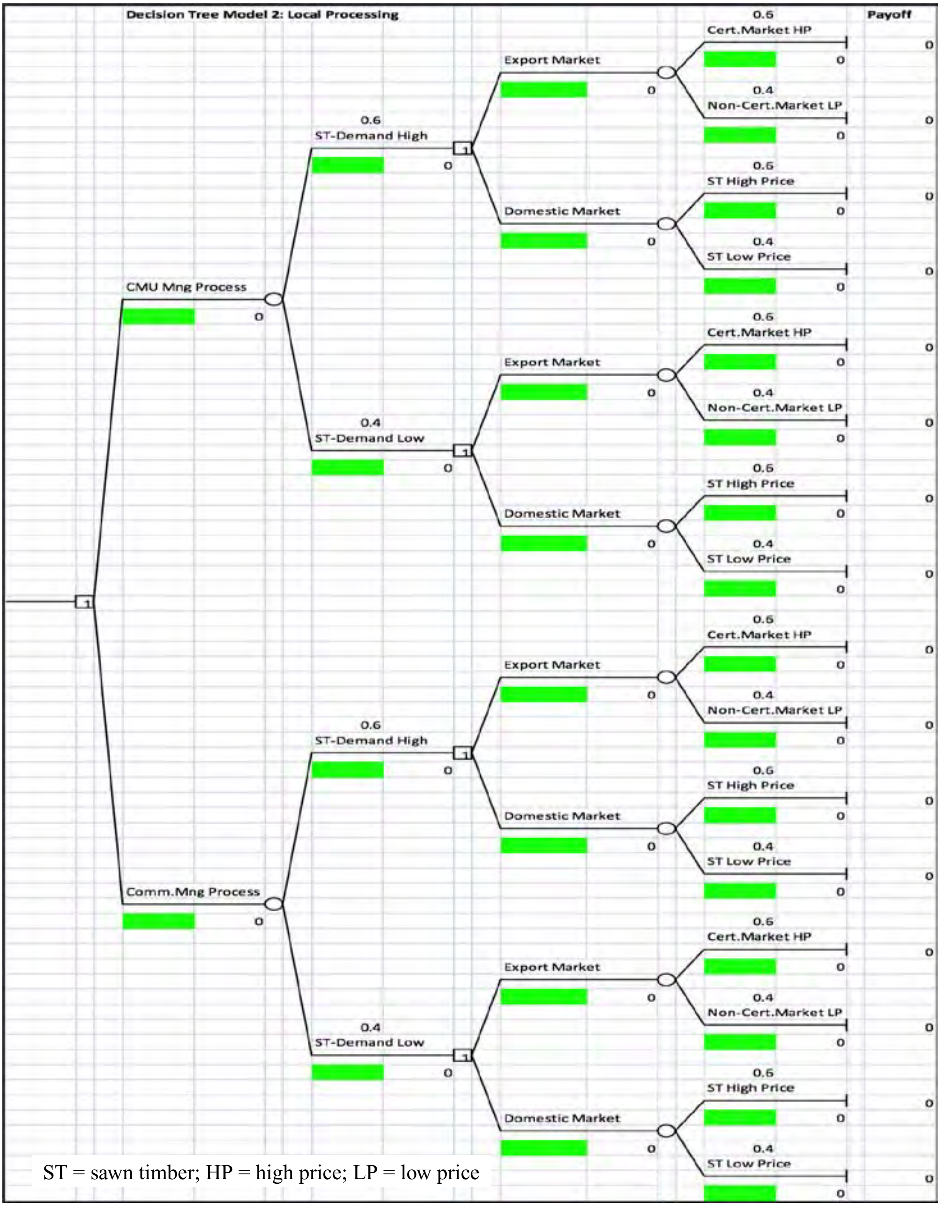



**Figure 3.** Main features of the decision-tree model

roll-back method to determine the EMV for each scenario being tested (Middleton 2001; Ragsdale 2008). In the analysis the management arrangement and type of market are the decision alternatives, while the sawn timber demand and market prices are uncertain events (Figure 3). The first two decision alternatives analysed using the decision tree were CMU-managed processing and community-managed processing. Initially, the decision-maker encounters the first two uncertainties—high or low sawn timber demand (ST-Demand High, ST-Demand Low); the second alternative decisions to be considered are sawn timber production for Export Market or Domestic Market. After a decision has been made, the last uncertainties (events) encountered are selling sawn timber at high or low prices in both export and domestic markets. In the export market, prices for sawn timber are high in a certified market and low in a non-certified market. In the domestic market, sawn timber prices are either high or low (Figure 3). The current average price for sawn timber in an overseas certified market is about K2,400/m³ (PNG kina); for example, when sawn timber is sold by PNG communities to Woodage Ltd in Sydney (Grigoriou and Keenan 2009; Keenan et al. 2010). This price is almost three to four times the average price for sawn timber (K700) in the domestic market.

*Expected monetary value*

A decision-maker uses a roll-back method to determine the EMV for the decision he makes in each scenario. This process determines the decision with the highest EMV by starting with each payoff and working from right to left through the decision tree and computing the expected values for each node. An EMV with the highest value is the decision alternative that is expected to return the highest monetary return for a particular scenario being considered; in this case, an EMV represents profit values.

To select the decision alternative with the highest EMV, the following equation (1) was used (Ragsdale 2008):

$$EMV_i = \sum_j r_{ij} p_j \qquad (1)$$

where: $r_{ij}$ is the payoff for alternative $i$ under the $j$th state of nature; $p_j$ is the probability of the $j$th state of nature.

*Application of the decision-tree model at the case study sites*

To apply the model, the local processing scenario has been tested using data available from the case study sites. The two decision alternatives considered in the analysis are CMU-managed processing (Table 1) and community-managed processing (Table 2) in a community-based local processing project.

**Table 1.** Production and marketing requirements in central marketing unit managed processing

| Decision alternative 1 |
|---|
| Local processing is managed by a community entity referred to as the central marketing unit (CMU) with mechanised equipment and increased capacity and production for the export market. The following production and marketing requirements apply:<br>• 1 × Lucas mill, 2 × Stihl 90 chainsaw + accessories<br>• 1 × 4WD truck, Hino FT/GT 500 series<br>• 1 × 4WD tractor, Massey Ferguson-72HD<br>• 400 m³ of logs harvested in 8 productive months<br>• at 50% recovery, production of 200 m³ sawn timber in 8 productive months<br>• seven-man team on wages @ K80/m³<br>• 10% increase in fuel and oil consumption @ K132/m³<br>• transport of sawn timber to wharf for export market @ K255/m³<br>• sawn timber sold to overseas certified market @ K2,400/m³ and community-based Fair Trade (CBFT) market @ K1,500/m³<br>• other costs for certification:<br>– certification requirements @ K50/m³<br>– fumigation @ K720, one-off payment<br>– wharf-handling fees @ K950, one-off payment<br>– Customs clearance @ K330, one-off payment |

**Table 2.** Production and marketing requirements in community-managed processing

| Decision alternative 2 |
| --- |
| Local processing is managed by the community itself with light equipment and limited capacity for the export market. The following production and marketing requirements apply:<br>• 1 × Lucas mill, 1 × Stihl 90 chainsaw + accessories<br>• 100 $m^3$ of logs harvested in 8 productive months<br>• at 50% recovery, production of 50 $m^3$ sawn timber in 8 productive months<br>• seven-man team on wages @ K80/$m^3$<br>• 5% increase in fuel and oil consumption @ K126/$m^3$<br>• transport of sawn timber to wharf for export market @ K255/$m^3$<br>• sawn timber sold to overseas certified market @ K2,400/$m^3$ and community-based Fair Trade (CBFT) market @ K1,500/$m^3$<br>• other costs for certification:<br>– certification requirements @ K50/$m^3$<br>– fumigation @ K720, one-off payment<br>– wharf-handling fees @ K950, one-off payment<br>– Customs clearance @ K330, one-off payment |

### Sensitivity analysis

An Excel add-in called SensIt (see Coote and Fox 2011) was used to carry out sensitivity analysis to examine the sensitivity of the EMV before the decision alternative is implemented. The analysis was carried out in two parts. The first analysis examined how sensitive the recommended decision was to the estimated probabilities. Sensitivity data represent the estimated probabilities in the decision tree in relation to the EMV; for example, when the probability of high sawn timber demand (HD) is 0.5, the EMV will be K7,800 under the CMU-processing scenario (Table 3).

The second analysis determined how sensitive the recommended decision was to changes in the input values (cash flow) in the decision tree (Ragsdale 2008). The expected input variables in the decision tree that are likely to have an impact on the EMV are the costs and income associated with the two decision alternatives (CMU-managed and community-managed processing). The absolute variable in this type of analysis is the input value (e.g. starting capital) multiplied by the range in percentage as set (e.g. ±10% or ±20%). In this study the absolute variables are negative for costs and positive for income associated with each decision alternative (Figure 2). In the results section, SensIt was used to generate tornado and spider charts to summarise the impact on the decision tree's EMV of each input value being set at ±10% and ±20% of the original value, in this case the EMV (base case) (Table 4).

## Results

### Current forest uses and future forest-management options

At the two case study sites, the local people were currently using some of their forests for small-scale harvesting, while still maintaining other forest lands for traditional uses such as hunting and gardening (Figure 4). The main forest-management options for the future preferred by the communities in both sites included reforestation, local processing, carbon trade, conservation and sawn timber export (Figure 5).

### Scenario indicators

A chi-square test for the different forest-management options and preference levels of 11 individuals interviewed (Table 5) shows high frequencies for local processing, small-scale harvesting and management for carbon values. Frequencies recorded in this case represent the total number of persons under each level of preference for a particular forest-management option at the two case study sites. Chi-square tests showed that there was evidence of association ($P$=0.016) (Table 5) between the forest-management options (scenarios) and the preference levels of individuals interviewed in the two case study sites.

The observed frequencies are high for high preferences for 'small-scale harvesting', 'local processing' and 'management for carbon values', while the observed count for no preference was high for 'log export'. For the 'no-harvesting' scenario, the observed count was high for 'not sure'. The frequency recorded for no preference was high (6 counts) for the 'log export' scenario (Figure 6).

Village meetings, discussions and interviews carried out at the two case study sites (Yalu and Gabensis villages) provided evidence that lack of social services, including education, health, community infrastructure and church facilities, influenced community interest in engaging in small-scale timber harvesting (Figure 7). In this case the cash income from the sale

**Table 3.** Pay-off matrix and EMV decision rule

| Scenario | Sawn timber demand (PNGK) | | |
|---|---|---|---|
| | HD | LD | EMV1 |
| CMU processing | 127,800 | –112,200 | 31,800 |
| CM processing | –65,494 | –125,494 | –89,494 |
| No harvest | 0 | 0 | 0 |
| Probability | 0.6 | 0.4 | |
| | (PNGK) | | |
| | EMV CMU | EMV CM | EMV none |
| Probability HD | 31,800 | –89,494 | 0 |
| 0.0 | –112,200 | –125,494 | 0 |
| 0.1 | –88,200 | –119,494 | 0 |
| 0.2 | –64,200 | –113,494 | 0 |
| 0.3 | –40,200 | –107,494 | 0 |
| 0.4 | –16,200 | –101,494 | 0 |
| 0.5 | 7,800 | –95,494 | 0 |
| 0.6 | 31,800 | –89,494 | 0 |
| 0.7 | 55,800 | –83,494 | 0 |
| 0.8 | 79,800 | –77,494 | 0 |
| 0.9 | 103,800 | –71,494 | 0 |
| 1.0 | 127,800 | –65,494 | 0 |

PNGK = PNG kina; HD = high demand; LD = low demand; EMV = expected monetary value; CMU = central marketing unit; CM = community managed

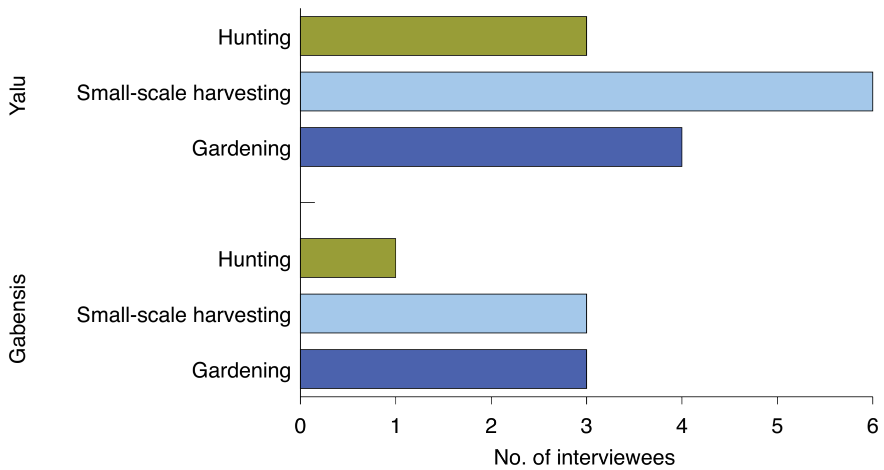



**Figure 4.** Current main forest uses by village—results preview

**Table 4.** Sensitivity analysis data

| Input description | | Variation 10% | Variable range | | |
|---|---|---|---|---|---|
| | | abs var | –var | base case | +var |
| Lucas mill | 85,000 | 8,500 | 76,500 | 85,000 | 93,500 |
| Chainsaw | 6,000 | 600 | 5,400 | 6,000 | 6,600 |
| Wages, manager | 80 | 8 | 72 | 80 | 88 |
| Wages, mill operator | 80 | 8 | 72 | 80 | 88 |
| Fuels & oil—CM (K/m³) | 126 | 12.6 | 113.4 | 126 | 138.6 |
| Maintenance & repairs—CM (K/m³) | 73.5 | 7.35 | 66.15 | 73.5 | 80.85 |
| 4WD truck—CMU | 260,000 | 26,000 | 234,000 | 260,000 | 286,000 |
| 4WD tractor—CMU | 162,000 | 16,200 | 145,800 | 162,000 | 178,200 |
| Planer / Moulder—CMU | 100,000 | 10,000 | 90,000 | 100,000 | 110,000 |
| Breakdown saw—CMU | 50,000 | 5,000 | 45,000 | 50,000 | 55,000 |
| Cross-cut saw—CMU | 50,000 | 5,000 | 45,000 | 50,000 | 55,000 |
| Fuels & oil—CMU (K/m³) | 132 | 13.2 | 118.8 | 132 | 145.2 |
| Maintenance & repairs—CMU (K/m³) | 77 | 7.7 | 69.3 | 77 | 84.7 |
| Transport local market (K/m³) | 60 | 6 | 54 | 60 | 66 |
| Transport wharf/export (K/m³) | 255 | 25.5 | 229.5 | 255 | 280.5 |
| Certification requirements (K/m³) | 50 | 5 | 45 | 50 | 55 |
| Fumigation | 720 | 72 | 648 | 720 | 792 |
| Wharf handling | 950 | 95 | 855 | 950 | 1,045 |
| Customs clearance | 330 | 33 | 297 | 330 | 363 |
| Sawn timber price—domestic market (K/m³) | 700 | 70 | 630 | 700 | 770 |
| Sawn timber price—certified market (K/m³) | 2,400 | 240 | 2,160 | 2,400 | 2,640 |
| Sawn timber price—noncert. market (K/m³) | 1,500 | 150 | 1,350 | 1,500 | 1,650 |
| Sawn timber production—CM (m³/year) | 50 | 5 | 45 | 50 | 55 |
| Sawn timber production—CMU (m³/year) | 200 | 20 | 180 | 200 | 220 |
| No. of fortnights (per 8 productive months) | 16 | 1.6 | 14.4 | 16 | 17.6 |

CM = community managed; CMU = central marketing unit

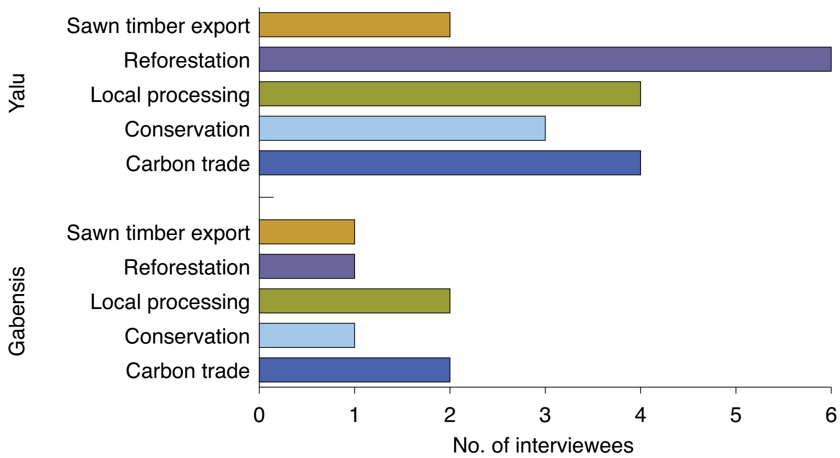



**Figure 5.** Future forest-management options by village—results preview

**Table 5.** Chi-square statistics for the different forest-management options and preference levels of individuals interviewed

| Chi-square test: high preference, low preference, no preference, not sure | | | | | |
|---|---|---|---|---|---|
| Expected counts are printed below observed counts. | | | | | |
| Chi-square contributions are printed below expected counts. | | | | | |
| | High preference | Low preference | No preference | Not sure | Total |
| 1 | 4 | 5 | 1 | 1 | 11 |
| | 3.40 | 2.80 | 2.60 | 2.20 | |
| | 0.106 | 1.729 | 0.985 | 0.655 | |
| 2 | 6 | 3 | 1 | 1 | 11 |
| | 3.40 | 2.80 | 2.60 | 2.20 | |
| | 1.988 | 0.014 | 0.985 | 0.655 | |
| 3 | 1 | 1 | 6 | 3 | 11 |
| | 3.40 | 2.80 | 2.60 | 2.20 | |
| | 1.694 | 1.157 | 4.446 | 0.291 | |
| 4 | 5 | 4 | 1 | 1 | 11 |
| | 3.40 | 2.80 | 2.60 | 2.20 | |
| | 0.753 | 0.514 | 0.985 | 0.655 | |
| 5 | 1 | 1 | 4 | 5 | 11 |
| | 3.40 | 2.80 | 2.60 | 2.20 | |
| | 1.694 | 1.157 | 0.754 | 3.564 | |
| Total | 17 | 14 | 13 | 11 | 55 |
| Chi-square = 24.779, DF = 12, *P*-value = 0.016 | | | | | |
| 20 cells with expected counts less than 5 | | | | | |

Forest-management options: 1 = small-scale harvesting, 2 = local processing, 3 = medium-scale log export, 4 = carbon trade, and 5 = no harvesting

of sawn timber is needed to meet basic needs such as food and clothing, and the building of infrastructure in the community.

The factors influencing a family's engagement in small-scale timber harvesting included lack of income for sending children to school and better homes. Sawn timber demand, timber price, certification benefits and markets influenced local people's commercial interest in engaging in small-scale timber harvesting in the two communities (Figure 7). While there was a lack of cash for all purposes (including for savings) to purchase the required equipment for harvesting (e.g. a Lucas mill), local people were also interested in building community facilities from some of the sawn timber produced, as there was a lack of government assistance.

## Decision analysis output

The input of cash flow to the two decision alternatives (CMU-managed and community-managed processing) resulted in the CMU-managed processing returning an EMV of K31,800 in profit per year (Figure 8). In the community-managed processing, an EMV of K89,494 loss was estimated. The EMV in this analysis is dependent on the costs and income associated with each decision alternative that was input into the model.

For the export market, costs are associated with labour, operations (variable), transport to wharf and certification requirements, while in the domestic market, costs are for labour, operations and transport to the local market. The income obtained depends on whether the sawn timber is exported to a certified (high price) or non-certified (low price) market for export or local domestic sale (Figure 8).

## Sensitivity analysis outputs

Sensitivity analysis of the estimated probabilities in the decision tree in relation to the EMV shows that, as the probabilities increase, so will be the EMVs; for example, under the CMU-processing scenario (Figure 9). Analysis shows that when the probability for high sawn timber demand is 0.5, the associated EMVs increase under CMU-managed processing, while the EMVs under the community-managed processing are centred around negative values for all associated probabilities, representing losses (Figure 9).

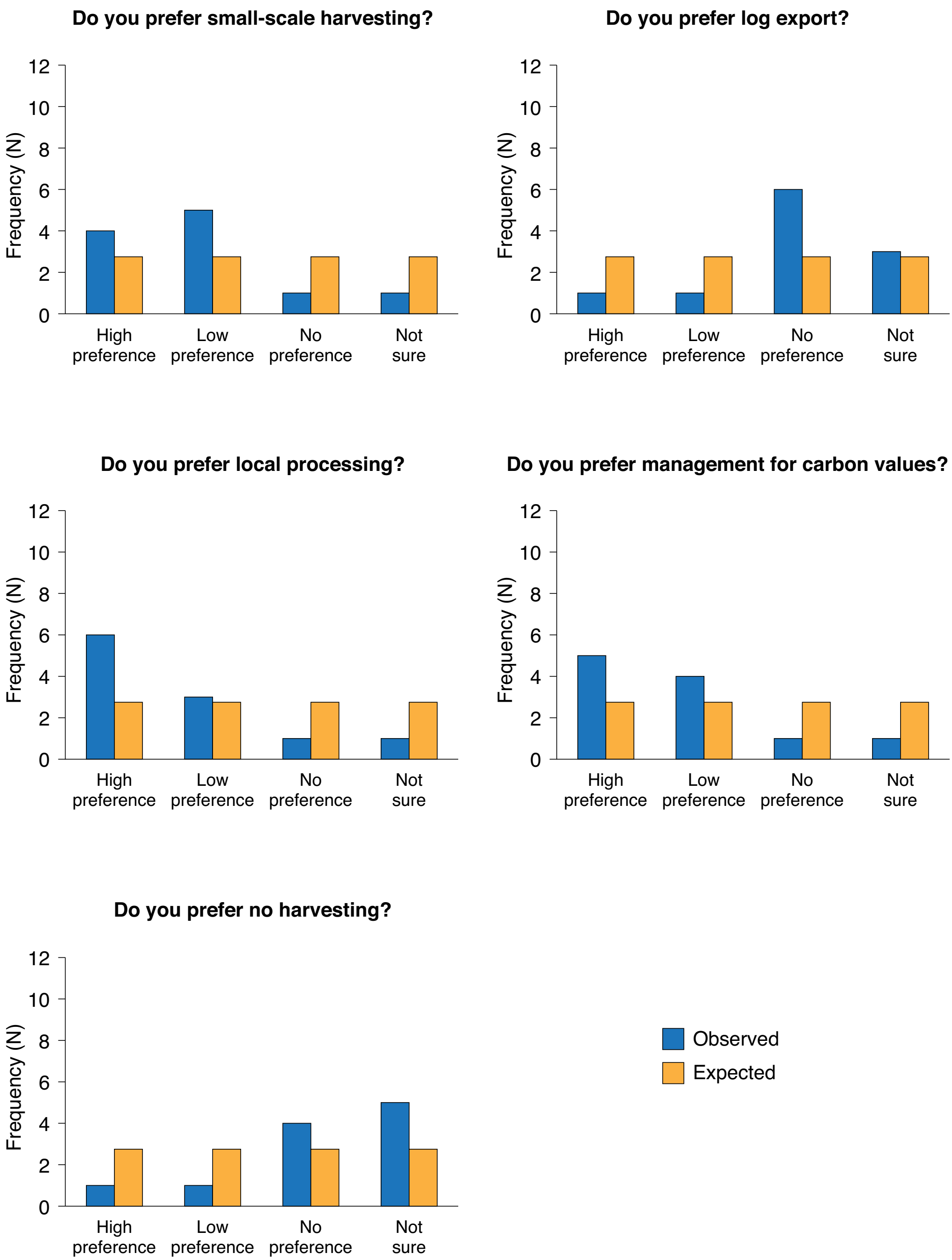



**Figure 6.** Graphical presentation of the frequencies of responses from field interviews

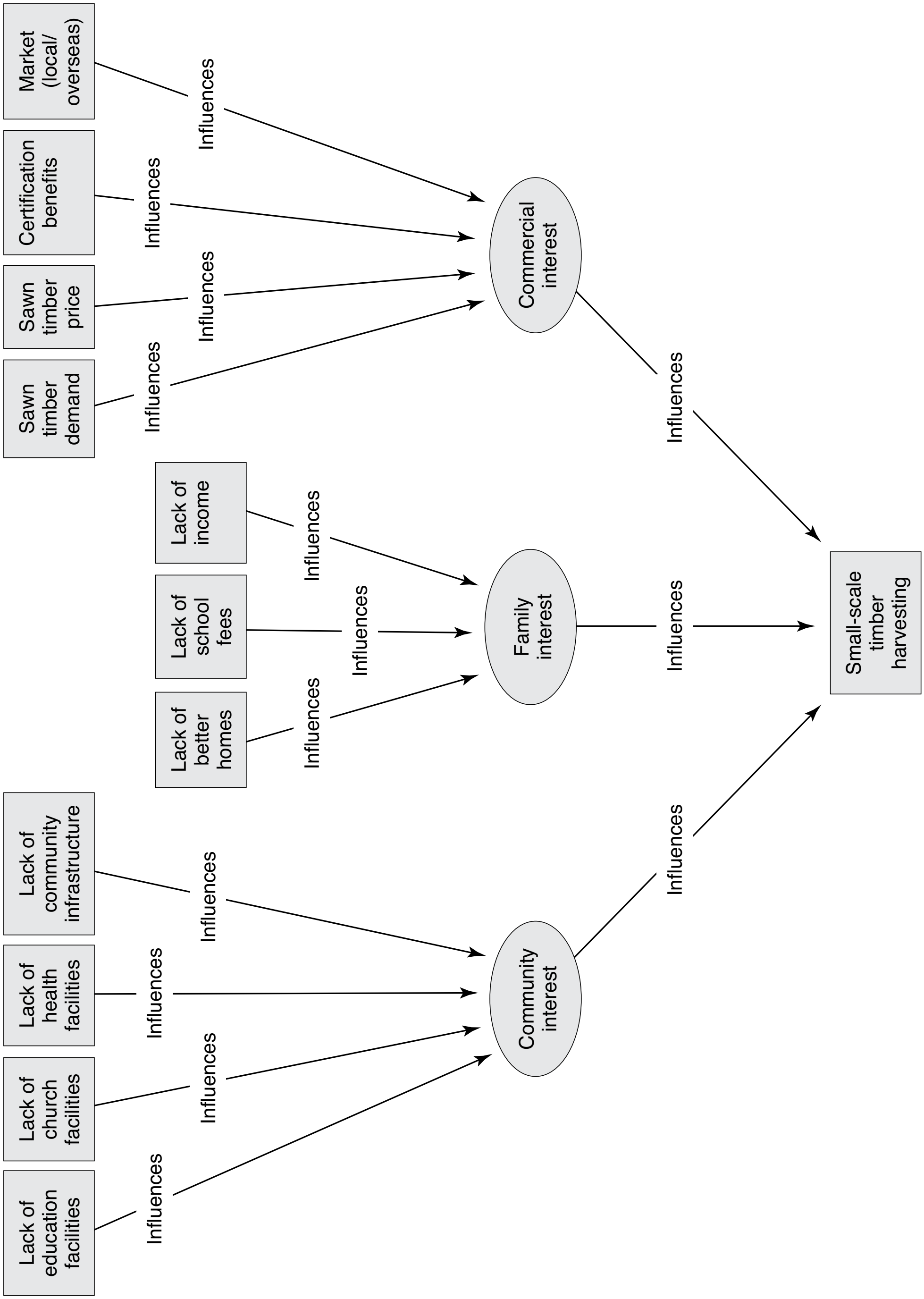
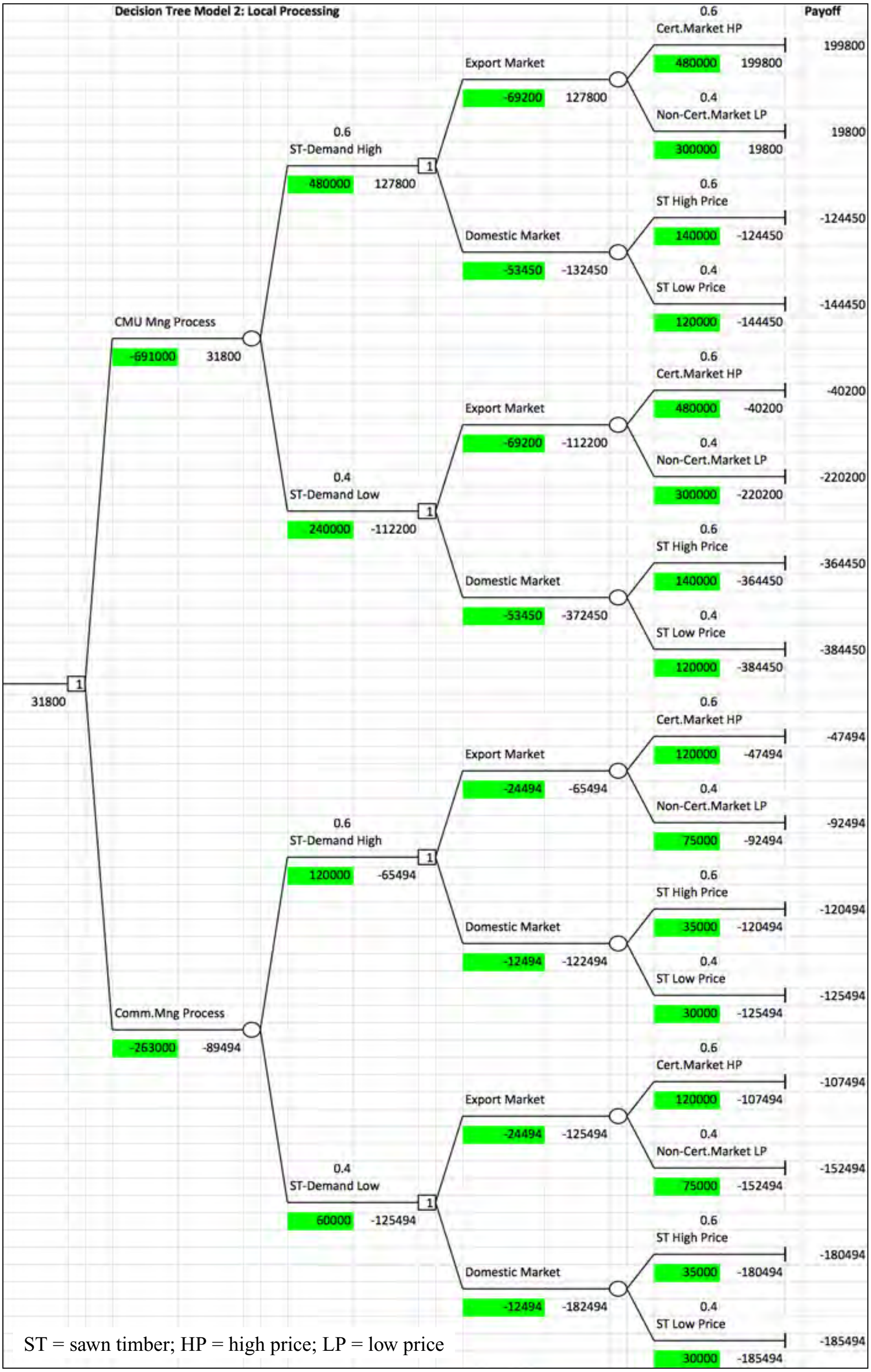



**Figure 7.** A model generated from the outcomes of the interviews showing the factors influencing community attitudes towards small-scale timber harvesting




ST = sawn timber; HP = high price; LP = low price

**Figure 8.** Decision-tree model—local processing

Sensitivity analysis indicated that annual sawn timber production and the sawn timber price in the certified overseas market in a CMU-managed processing scenario have the largest impact on the EMV's range, followed by the costs of purchasing a 4WD truck and tractor at ±10% of the EMV (Figure 10). Input variables in the decision tree with minimal impact on the EMV are not shown.

The spider chart (Figure 11) represents the same information as the tornado chart. Both annual sawn timber production and the sawn timber price in the certified overseas market in a CMU-managed processing scenario have the largest impact on the EMV's range, followed by the costs of purchasing a 4WD truck and tractor at ±10% of the EMV. In the analysis the sawn timber price differential is important—the high price in the certified market is justified as it has the second largest impact on the EMV. The inflection point where the associated lines representing each input variable meet in the chart (Figure 11) is when annual sawn timber production is expected to increase by 10%.

## Discussion

Evaluating scenarios for community-based forest management is a new approach to tropical forest management, requiring local people's participation in decision-making. This study suggests that communities in PNG lack the required information to make an informed decision on how they would like to manage their forests. However, given the appropriate skills and with the provision of proper management tools, local people can make an informed decision and expect maximum benefits from the management of their forest resources.

The study at the two case study sites (Yalu and Gabensis villages outside Lae, PNG) showed that local people's preference levels for small-scale harvesting, local processing and carbon benefits were high (Table 3; Figure 6). This was mainly because of a lack of income to improve their livelihoods; hence, communities wanted to get monetary benefits from forest-management options that generated an income, including small-scale timber harvesting (Figure 7).

A decision analysis tool developed in this study is a new technique in tropical forest management (Figure 8). The major goal of this technique is to assist the decision-maker determine the best decision when presented with different alternatives and future uncertainties (Middleton 2001).

Two Excel add-ins (TreePlan and SensIt) have been used to develop the decision-tree model and carry out sensitivity analysis on the output EMV (Middleton 2001; Ragsdale 2008). The application of this model using data from the case study sites shows that, when the two decision alternatives (CMU- and community-managed processing) were considered in a community forest-management project, the EMV returned for the CMU-managed processing is higher (K31,800) in profit terms, while the community-managed processing returns an EMV in the form of an estimated loss of K89,494 (Figure 8). Sensitivity analysis of the EMV shows that the annual sawn timber production is the model input that has the largest impact on the EMV, followed by the sawn timber price in the certified market at ±10% (Figures 10 and 11). In this case the profit is dependent on sawn timber prices for exports to certified and non-certified overseas markets. The price differential is justified, as sensitivity analysis provides evidence that prices in the certified market also have an impact on the profit (EMV). The application of the model is flexible in that, depending on the cash flow associated with each decision alternative, the EMV is determined by the related costs and income input into the model.

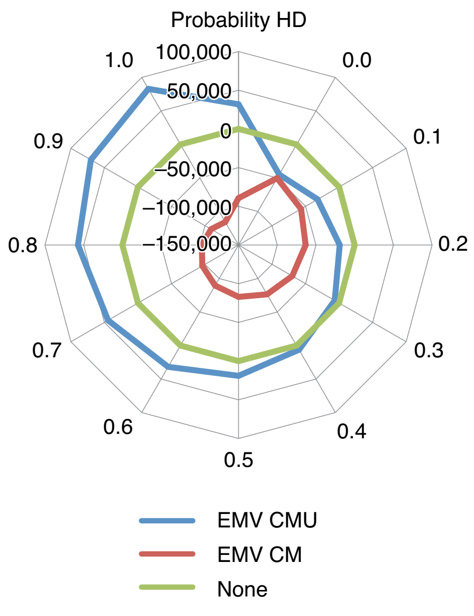



**Figure 9.** Radar chart showing the sensitivity of the decision alternatives

In PNG the benefits of certification have been recognised, and interest in adopting certification standards is increasing at the community level of forest management. However, the requirements for certification are very costly and time consuming, and community groups have very little capacity to comply with the standards and guidelines. Certification of village-based timber operations requires heavy subsidisation of not only the certification process, but also the subsequent production, transport and marketing of timber (Scheyvens 2009), and this is a major challenge in PNG. In our study it was recognised that the CMU entities operating in the pilot region have the potential to increase production and meet certification requirements in order to increase income from sawn timber exports to certified markets

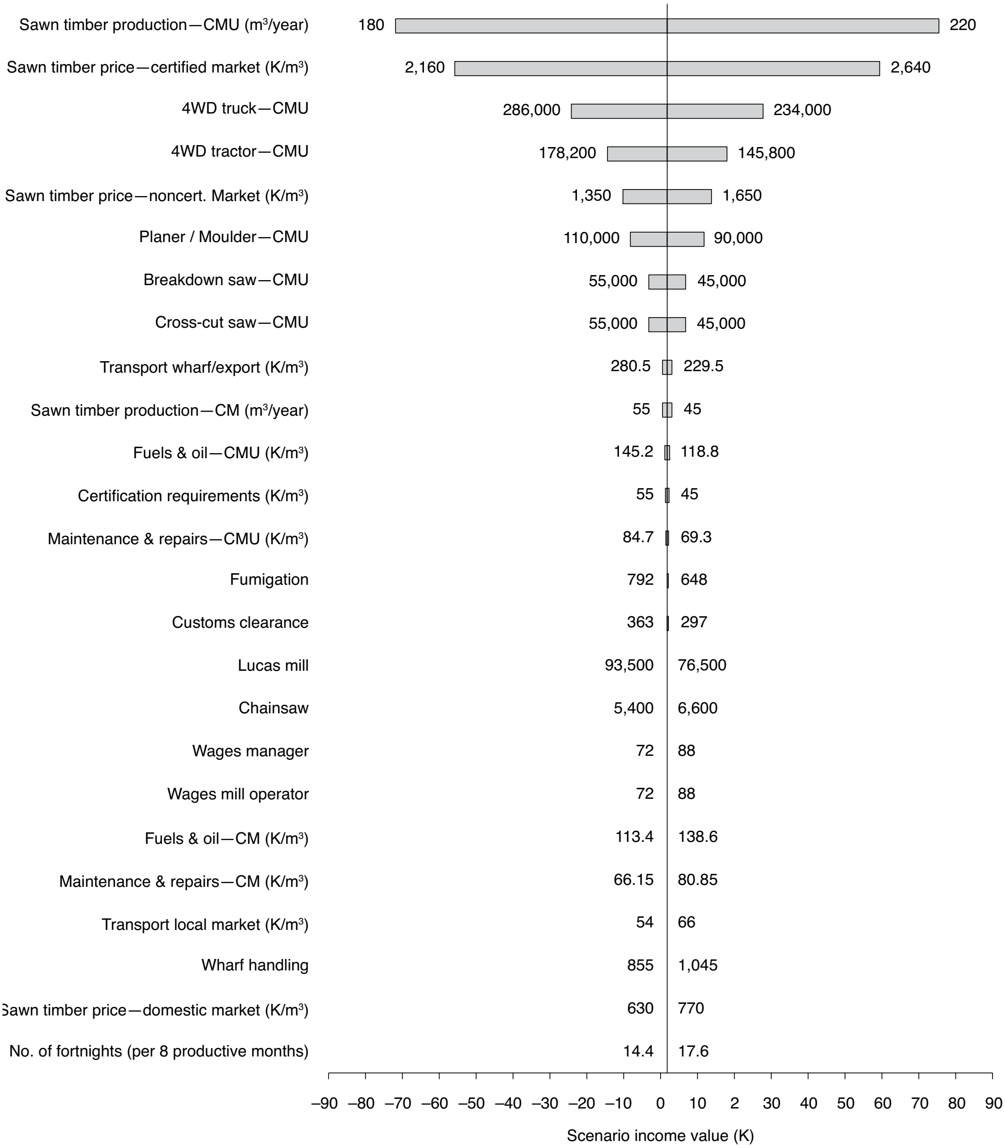



**Figure 10.** Tornado chart showing the sensitivity of the expected monetary value at ±10%

overseas. However, these entities lack management and leadership skills for operating a profitable business enterprise (Keenan et al. 2010). Application of the decision-analysis model in this study also showed that income from certification had an impact on the EMV. Thus, certification can be seen as an instrument to promote sustainable forest management (FSC 2005; Durst et al. 2006), and has the potential to increase income from the export of sawn timbers for communities in PNG, depending on the prices adopted in the models.

## Conclusion

Scenario evaluation for cutover forests is a new approach to tropical forest management and is appropriate in the context of community-based forest management in PNG. Given the complicated social structures and land-tenure systems in PNG, the PAR protocol involving the two communities in this study is also appropriate. The study involved community participation in the development of scenarios for the future management of their cutover forests.

The application of the decision-tree model developed in this study shows that, with very little capacity and high operational costs, a community-managed processing project is likely to make a loss. A CMU-managed processing facility can increase its capacity with the addition of mechanised equipment and increased production and, with a high sawn timber price in the certified market, could be expected to make a reasonable profit in 1 year.

The tools developed in this study are appropriate for community-based forest managed in PNG and can be applied in tropical forest management elsewhere in the region. A new policy direction relating to community forestry is therefore necessary in order to adopt the systems developed in this study in the future management and utilisation of cutover forests at the community level in PNG.

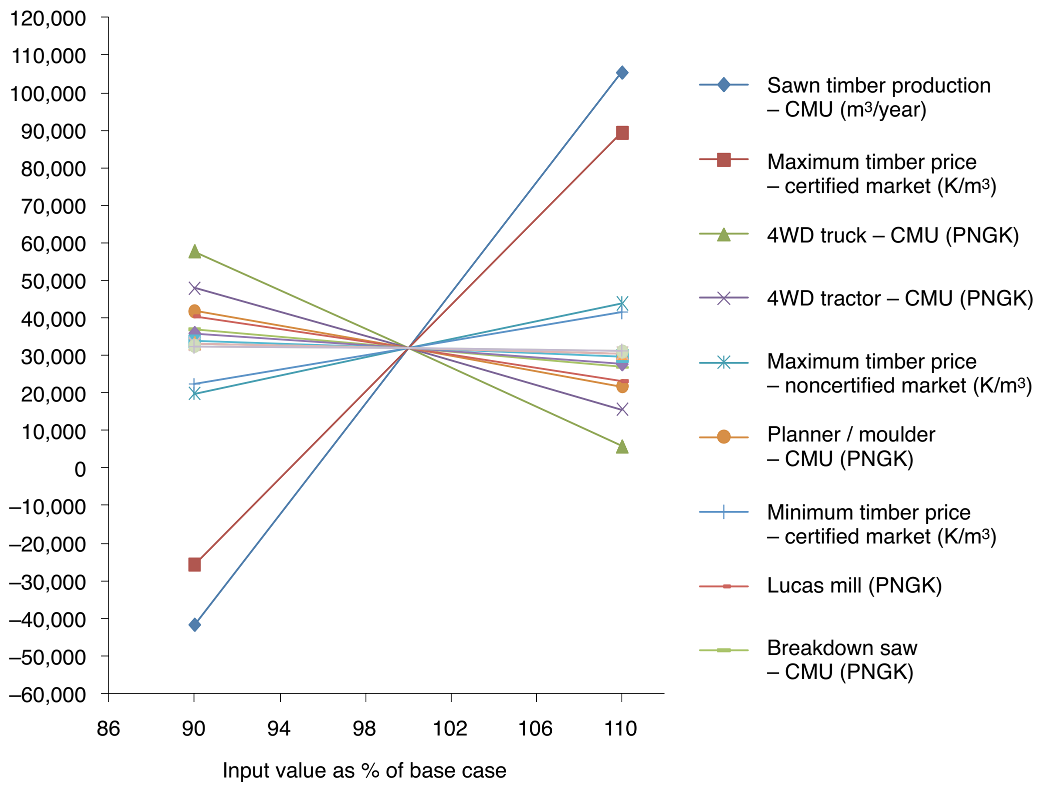



**Figure 11.** Impact of input variables on the expected monetary value at ±10% of the base case

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