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Sustainable plantation forestry in South-East Asia

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Cover: Dr Dang Thinh Trieu of the Vietnamese Academy of Forest Sciences discusses stand management with the owner of a smallholder plantation of acacia hybrid in central Vietnam. (Photo: Chris Harwood)

Foreword

Acacia and eucalypt plantations are vitally important to meeting the demand for wood products and for contributing to smallholder farmer livelihoods in many parts of the world. The area of acacia and eucalypt plantations in South-East Asia and southern China now exceeds 7 million hectares. Most of this area has been established within the past two decades, and most plantations are managed and harvested on short rotations of 5–8 years.

For the past 30 years, the Australian Centre for International Agricultural Research (ACIAR) has supported research on the domestication and improvement of acacia and eucalypt species for plantation forestry, because of their potential for fast growth and production of wood suitable for a variety of uses. Many candidate species were trialled and evaluated in the 1980s and 1990s in a variety of environments in South-East Asia. Today, genetically improved varieties of just three acacia and five eucalypt species, and some clonal interspecific hybrid varieties, dominate plantation forestry in this region. ACIAR has also supported research on pests and diseases and sustainable plantation management.

Plantations occupy only a small percentage of the total land area of each country, yet contribute much to household, regional and national economies of several South-East Asian countries. Logs from these plantations now provide much of the raw materials for the manufacture of paper pulp, composite and engineered wood products, and sawn timber in many countries. Future success and support for plantation forestry depends fundamentally on achieving sustainable production with due environmental care from the current plantations. While some authors question the sustainability of short-rotation plantation forestry, there are few published studies that have looked at this issue in a systematic manner across many countries.

This report reviews the state of knowledge and the current situation in plantation forestry in South-East Asia. The authors are leaders in their respective fields of science, who have worked in South-East Asia for many years. The multidisciplinary review utilises actual inventory data from successive rotations that were provided to the authors by plantation growers in five countries. It addresses the following interrelated questions:

- Can plantation productivity be sustained over successive short rotations?
- What are the prospects for increasing production?
- What are the challenges to, and the ways forward for, sustainable production?

The review emphasises that sustainability is not a destination but a journey, and that further research and creative partnerships between all stakeholders are required for successful progress. The synthesis of knowledge provided in this report, together with the identified research priorities and suggested ways forward, will assist developing countries and plantation owners to continuously improve sustainable plantation forestry in the region.

Nick Austin
Chief Executive Officer, ACIAR

Contents

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We acknowledge the contribution of companies who hosted our visits, shared information on management and discussed operational challenges. Several of them provided their confidential inventory data, and diligently responded to many queries in the course of the analysis. We hope that their contribution to the project will help them to identify opportunities to enhance the management of their plantations. We thank them for this unique collaboration and hospitality.

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All photos taken by report authors C.E.. Harwood and E.K.S. Nambiar unless credited otherwise.

Abbreviations

CSIRO	Commonwealth Scientific and Industrial Research Organisation
c.v.	coefficient of variation
MAI	mean annual increment
s.d.	standard deviation
SI	Site Index
SOC	soil organic carbon
SQ	Site Quality

Executive summary

South-East Asia has more than 7 million hectares of eucalypt and acacia plantations, mostly established during the past two decades and managed on short rotations (5–8 years). They are an important and expanding natural resource primarily for wood production, supporting value-adding local industries. They are managed mostly by corporate growers but, in some countries such as China, Thailand and Vietnam, small plantations owned and managed by individual households or small businesses comprise a significant proportion of the plantation area.

Despite the importance of these plantations, there is no systematic analysis of their productivity and the challenges for sustainable wood production. Partly because of this, concerns about sustainability are periodically raised in local and international forums. The Australian Centre for International Agricultural Research (ACIAR) and the International Finance Corporation (IFC) therefore commissioned Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO) to undertake this review. It is not an analysis of sustainability in the holistic sense, integrating economic, social and environmental values; it focuses on sustainable wood production, which is a foundation of sustainable forestry.

This report first presents a scientific review of the biophysical basis for sustaining wood production over successive rotations in tropical environments, focusing on genetic selection and improvement, challenges posed by diseases and pests, and site and stand management practices in South-East (SE) Asia. This is followed by brief reports on China, Indonesia, Malaysia, Thailand and Vietnam, where we visited plantation forests with managers and researchers and discussed management practices and challenges. Several companies provided substantial inventory data from commercial plantations, in confidence, for independent analysis. This provided a unique opportunity to examine productivity trends and variation at various levels. Finally, overall outcomes are synthesised and pathways towards sustainable forestry are suggested.

Significant investments have been made in developing and deploying genetically selected and improved planting materials in all countries. This technology has helped to reduce losses from some diseases and pests, and extreme climatic events such as cold spells. However, the extent to which use of improved genetic material increases estate-wide productivity is uncertain and seldom quantified. In some cases, genetic gains measured in experimental trials have not translated into yield increases at the estate level. Rigorous evaluation of the contribution of improved germplasm should underpin future breeding investments. Breeding objectives should prioritise the development of varieties resistant to serious pests and diseases, rather than raising expectations of unrealistic increases in growth rates. Establishing large areas of plantations using only one or two 'superior' clones, and transferring selected genetic materials across ecosystems and planting them operationally without rigorous local testing, have both led to serious plantation failures.

As plantation forestry has expanded, threats from new diseases and pests have increased. A striking case is the threat to acacia plantations in Indonesia and Malaysia in recent years. In response to widespread damage by diseases causing root rot and stem canker/wilt, and damage by monkeys and squirrels in some areas, companies in Sumatra and Sabah are changing species from *Acacia mangium* to eucalypts. This is a timely response and mirrors a similar transition in Vietnam in the late 1990s when *Eucalyptus camaldulensis*, which suffered from leaf diseases, was replaced by an acacia hybrid that was more productive and disease resistant. Remarkably, pests and diseases have so far been manageable elsewhere in SE Asia. However, their impact is likely to increase. The need for systematic vigilance and the importance of coherent national and international policies supporting research, quarantine and surveillance to pre-empt and manage these risks cannot be overemphasised.

Well-developed plantation management is central to production in both the short and long term. The inter-rotation phase from harvest to replanting and stand establishment is a critical period of risks and opportunities that determines the success of short-rotation forestry. There is unambiguous evidence that strategies to conserve soil and site organic matter and minimise site disturbance are key to sustaining production.

Companies in Indonesia have adopted practices that are helping to conserve site resources. Elsewhere, some current management practices are likely to degrade sites and threaten sustainability of short-rotation tropical forestry. Examples described in the report include bulldozing sites between rotations, leading to loss or displacement of organic matter and surface soils; burning of harvesting slash and other vegetation residues; and repeated ploughing several times per year as the only method of weed control. Following harvest of merchantable wood, export off-site of the remaining biomass including stumps for bioenergy, while it may seem attractive today, is likely to degrade sites.

Evidence from multisite research shows that, with sound management practices, productivity can be increased and sustained from the first to the second rotation while maintaining the productive capacity of the soil. Experimental evidence also dispels a commonly held belief that exotic species in monoculture degrade soils. Synthesis of evidence from many sites does not support this view. For example, the common but poorly substantiated conclusion in some reports that acacia plantations cause soil acidification is incorrect. The shorter the rotation length, the greater the need to refine and continuously improve soil management. Rather than being preoccupied with minimising wood costs in the short term, the principles of sustainability should be followed for enduring profitability. The challenge for forestry in many regions of SE Asia is to develop and apply integrated management practices with due care for landscape values and soils. The key to sustainability is sound and science-based management.

Productivity data from grower inventories allow some comparison of growth rates of successive crops in acacias but not for eucalypts. *Acacia mangium* in Sumatra had similar growth rates for two rotations, and second-rotation crops of acacias in Vietnam yielded as much or substantially more than the first rotation. One striking feature of the data is the high variation in growth rates for all species and hybrids at various scales of management. This applies even where single clones are planted across a compartment or landscape. Yet, there is very little quantitative understanding of how landscape factors, soils and management determine productivity. These issues are critical for eucalypts because, unlike acacias, they do not fix atmospheric nitrogen and thus nitrogen demands on site and dependence on fertilisers will be high. Thus, inventory data remain unexplored beyond their use as a stocktake for determining day-to-day harvesting and wood flow planning. In order to develop reliable management practices for increasing and sustaining production, organisations must invest in relevant research, beyond traditional fertiliser trials, to understand constraints to productivity and ways to increase it as a matter of priority.

The state of research and development (R&D) capacity varies widely in SE Asia. Big companies in Indonesia have capacity, although its effectiveness is not clear. In contrast, R&D capacity in some countries remains very weak, especially in the key area of soil management. One notable and serious issue in all cases is the weak linkage between public and private institutions. Consequently there is a lack of partnerships bound by a strong culture of application of research results and delivery of positive and measurable impacts. Thus, even well-established principles of sustainable management and practices proven to be successful in other countries remain poorly recognised and understood in some parts of SE Asia.

Sustainable outcomes are achieved not by any single solution or technology but through systematic application of an integrated package of science-based practices over time, consolidating incremental progress.

Some priority areas for coordinated and cooperative ventures necessary for plantation forestry to achieve its potential in SE Asia are highlighted in Chapter 6: *Ways forward*. They include more effective use of inventory data to document and help understand spatial and temporal patterns of productivity variation, improvements in harvesting and inter-rotation management practices in many regions to protect site resources, changes to vegetation management in some regions to avoid repeated inter-row ploughing for weed control, and collaborative research to overcome major disease and pest threats.

The needs of smallholder farmers who contribute much to national wood production, for example in

Vietnam and Thailand, are not well understood and advanced. Their needs are different from those of corporate growers, and their constraints deserve targeted support, especially for improving the productivity and quality of wood they grow and the returns they receive. With proper investments, their woodlots can be more productive and profitable and thus become a pathway towards reducing rural poverty.

In summary, development of SE Asia's acacia and eucalypt plantations is a significant achievement in building a natural, renewable and value-adding resource for the region. The diversity of biophysical attributes, management, business models and culture is such that there is no single common conclusion that can be drawn about their current level of productivity, or about their future prospects for sustainable production. Several region-specific threats and opportunities are identified in this report. A successful plantation forest future can be secured only by moving away from potentially unsustainable management practices and developing and applying integrated, science-based operational management systems.

1 Introduction

Plantation forestry based on short rotation cycles with acacias and eucalypts has expanded during the past two decades in South and South-East Asia, notably in southern China, Indonesia, Malaysia, Thailand and Vietnam. These are the countries and regions of focus in this report. To improve readability, we refer to them as 'SE Asia' while recognising that there are other countries in SE Asia that we were not able to cover. The region also has extensive plantations of other species including *Falcataria mollucana*, *Gmelina arborea*, *Swietenia macrophylla* (mahogany) and *Tectona grandis* (teak) managed under various rotation lengths.

South and SE Asia have 25.6 million hectares of planted forests, representing 8.7% of their total forest area (FAO 2010). Most of these forests (90%) are in China, India, Indonesia, Malaysia, Thailand and Vietnam. China has more than 4 million hectares of eucalypt plantations. An estimate of the area of acacia and eucalypt plantations in the countries and regions reviewed in this report is provided in Table 1. For China, data show only the two provinces covered in our study. In general, plantation forests cover only a small proportion of the total land area in these countries.

1.1 Scope and objectives

This study aims to review and synthesise relevant scientific information to evaluate the prospects for sustainable wood production over multiple rotations of short-rotation acacia and eucalypt plantations in SE Asia. It is not an assessment of plantation forestry covering all the areas in these countries at the national level, although the results and discussions are provided under the country names for convenience. We have focused on selected areas within countries, as follows: China (Guangxi and Guangdong provinces in southern China), Indonesia (south and central Sumatra), Malaysia (Sabah), Thailand (central) and Vietnam (northern, central and southern). Plantations in Laos were also visited in the course of the project. Large-scale eucalypt plantation forestry there is new, productivity data are not yet available, and developments are mainly around agroforestry. However, the visit confirmed that Laos faces some plantation management issues similar to those in neighbouring Thailand.

This study is about plantation forests established for wood production in 5–10-year rotation cycles. Trees grown outside plantations in rural landscapes

Table 1. Estimates of current areas of acacia and eucalypt plantations in countries/regions covered in this report

Country (region)	*Acacia* (ha)	*Eucalyptus* (ha)	Total land area (million ha)
China (Guangdong and Guangxi provinces only)	<50,000	3,350,000	41.5
Indonesia	1,200,000	300,000	192.9
Malaysia	250,000	20,000	33.0
Thailand	<20,000	500,000	51.2
Vietnam	1,100,000	200,000	33.2

Source: GIT Consulting's world eucalyptus map (http://git-forestry.com/download_git_eucalyptus_map.htm) and recent government and company statistics obtained by the authors.

(such as roadside and boundary row plantings and scattered trees on farms) play an important role in land use, but the scope of this review did not permit an analysis of those resources. Nevertheless, the biophysical analysis presented here would be relevant to the management of on-farm tree resources.

Most acacia and eucalypt plantations are intended to grow and deliver wood for the wood-processing industries. Most of the wood is used for domestic paper pulp production or export of woodchips for pulping elsewhere. However, use for sawn timber, veneer and composite products (such as medium-density fibreboard) is increasing. In Vietnam, acacia wood is used for furniture making. Poles for construction work are another use.

Regardless of the size of the companies or growers or the purpose of the wood, high rates of wood production, sustained over successive rotations, provide the foundation for successful plantation forestry and for the processing industries that provide income and employment to many rural regions of SE Asia.

Sustainability in the broader sense is a multidimensional concept, taking into account many values. In the context of plantation forestry, these values include productivity; environmental values including water, biodiversity and carbon sequestration; economic and social benefits to the community; and profit to investors. This review focuses on the biophysical factors influencing sustainable wood production over successive rotations.

Many concerns have been expressed about the sustainability of short-rotation plantation forestry in SE Asia that is intensively managed and based on exotic species (Cossalter and Pye-Smith 2003). Acacia and eucalypt plantations now occupy about 7 million hectares in the regions covered by our review, with large areas moving into successive rotations. Apart from the limited data from experimental plots, there is no consolidated account of the productivity of short-rotation plantations in the region. There is, therefore, a timely need and opportunity for a review of the biophysical performance of short-rotation forestry as a productive and sustainable land use in the tropical environments of SE Asia.

The core objectives of this project were to:

(i) review the current scientific understanding of biophysical processes determining productivity
(ii) evaluate the challenges to production in each of the regions studied
(iii) apply the findings to identify research and development (R&D) priorities, and assist managers to refine evidence-based management for wood production balanced with environmental care.

1.2 Methodology

Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO) has more than 25 years of experience of plantation forestry in SE Asia, based on research and training partnerships with both public and private organisations. Based on that record, this project was commissioned and partly funded by the Australian Centre for Agricultural Research (ACIAR). The International Finance Corporation (IFC) provided additional funds that enabled further field work and collaboration with growers to be undertaken. These contributions enabled CSIRO to undertake this review.

This study used a set of interrelated approaches, confined to acacia and eucalypt plantation productivity:

- a review of the relevant scientific information on the processes that determine sustainability of wood production over multiple short rotations, and especially the way inter-rotation management affects production
- field visits by the authors to the regions, supported and guided by local scientists and managers, to understand the current management practices (their strengths and weaknesses), as well as discussion of opportunities and challenges with plantation managers
- collection, collation and analysis of wood inventory data from companies to examine trends in production over one or more rotations
- synthesis of this information, identifying major issues and formulation of recommendations for future research and management.

We contacted the relevant public and private companies (listed in the acknowledgments) and sought their collaboration, with the undertaking to protect the commercial confidentiality of the raw inventory data and the links between data and individual donors of the data. All field visits were guided by local managers enabling in-depth discussions. In return, we shared our understanding of various issues from a global perspective and provided informal advice on a range of issues at field sites. In several cases, this advice was followed up with informal written comments. This fostered significant interaction and indeed trust. During the data analysis by CSIRO, inventory staff in respective organisations responded positively to questions about anomalies, accuracy and the various other details inevitable and inherent in the thousands of data entries collected by many staff over space and time.

There are important issues that are not covered here. The sustainability of plantations established on peat ecosystems is not examined. Peat systems have unique challenges that require attention, but were outside the scope of this review. Also the impacts of plantation forests on environmental values including water and biodiversity are not reviewed. Readers are referred to a new synthesis on forestry in the global context (Sands 2013), and to the chapter therein on plantations for wood production with environmental care (Nambiar and Sands 2013).

This report is arranged as follows:

- Chapter 2: Sustainability in context
- Chapter 3: A multidisciplinary review of the biophysical determinants and management of sustainable wood production
- Chapter 4: Country reports: assessments of practices and challenges in each of the regions
- Chapter 5: Productivity: trends and variations
- Chapter 6: Ways forward.

We hope that this review will inform forest growers about the critical considerations underpinning sustainable production, and will stimulate discussions and further action and achievement in science-based management practices both within the organisations that contributed to this work and more widely across the region.

2 Sustainable production in context

2.1 Some concepts

Productivity is the foundation of sustainable plantation forestry. This is so, even when forest systems are designed to provide environmental services, because productivity and ecological processes including carbon sequestration, mineral cycling, hydrology and biodiversity are inseparably interconnected. Sustained productivity is, arguably, the best measure that integrates the functioning of planted forests, and changes in productivity signal the direction of changes in response to management practices and ecological events including climate change.

Sustainability can be judged by the degree of alignment among relevant and critical variables described in the conceptual model in Figure 1. The variables in the figure are illustrative examples and there are others that may assume importance according to local circumstances and overall goals. For example, social and community values, biodiversity and water are important considerations for sustainability in the holistic sense. This figure illustrates how a set of variables interacts with the pursuit of sustainable production. Critical interactive variables include ecological capability and limits of the site, including soil and water and their interconnection with the landscape, species and their genetic potential, and management intensity. The drift to risk or the journey to success depends on the degree of alignment, weak or strong, between the components (Figure 1). The risks to sustainability may be biological (e.g. as currently posed by the severe impact of fungal diseases in *Acacia mangium* in Indonesia, see Section 4.1) or may be due to faulty business models, for example the managed investment schemes for eucalypt plantations in Australia (Nambiar 2010; Semple 2013). Management choices that induce risks include choice of the wrong species, practices that deplete or degrade soil, over-cutting plantations at decreasing rotation length, and inadequate attention to community expectations.

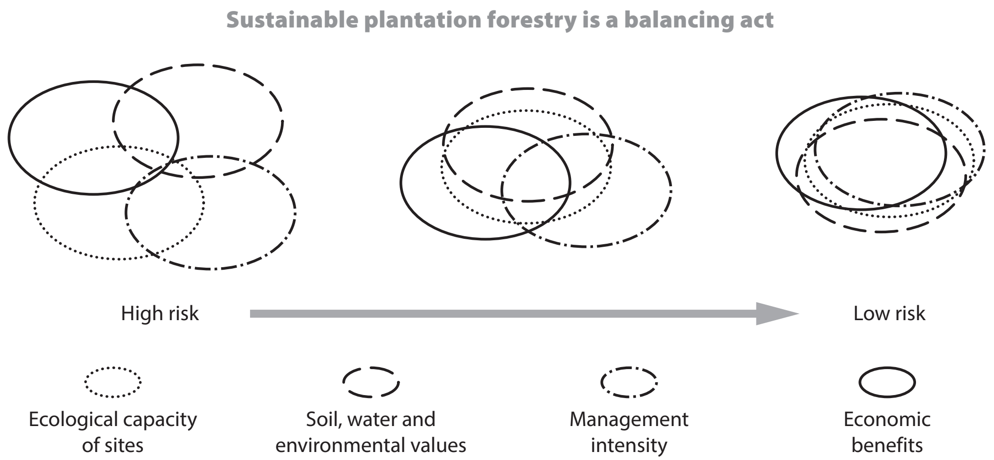

Figure 1. Interactive variables and their alignment in relation to the degree of risks to sustainable plantation forestry (from Nambiar 1996)

The alignment of variables in Figure 1 cannot be perfect because, as with any human enterprise, it is not possible to achieve the full knowledge, tools, investment and social agreement necessary for perfection. Sustainability has therefore been described as a journey, not a destination. Management or natural events (e.g. drought) will continuously influence the direction between the high and low risks. The goal of management should be to avoid high-risk management practices and continuously strive towards the best alignment.

To achieve sustainable outcomes, plantation forestry developments should be guided by clear goals. Nambiar (1999) proposed the following goals:

- ensure the trend in productivity is non-declining, or increasing over time
- protect the productive capacity of the soil and off-site values including water and biodiversity in the landscape
- promote incentive, innovation and profit in growing and utilising wood
- share and improve the economic and social benefits to the community.

Thus, for success, a forestry enterprise must be backed by a holistic approach to management.

If productivity is static or not sustained (i.e. productivity per unit area is declining) across a sizeable part of the estate and a wood-processing plant (e.g. a pulp mill) depends on wood supply from planted forests, there is a risk of one or more of the following economically and ecologically undesirable consequences (Nambiar and Sands 2013):

- the plantations may be over-cut (i.e. the amounts of wood harvested annually from clear-cut stands exceed the net cumulative growth gained by the remaining stands)
- the rotation length may be reduced further to meet the urgency of the day
- dependency on unsustainable harvests from native forests may continue, as well as clearing and converting degraded or secondary mixed-species native forests.

2.2 Short-rotation forestry: opportunities and risks

Historically, plantation forests in the temperate regions of the world have been managed through harvesting cycles in timescales of decades. Even in the tropics and subtropics, some plantation species are managed over long (25+ year) rotations, for example, teak in Java and India, and hybrid pine in Queensland, Australia. Short-rotation plantation forests represent a relatively new venture in forest management and are mostly in subtropical and tropical environments. Acacia and eucalypt plantations in SE Asia started to expand rapidly in the 1980s in response to the demands for large-scale wood supply. There was an expectation that they would lessen the pressure on native forests as a source of wood for forest product industries. Many nations continue to encourage investments in acacia and eucalypt plantations as a path to economic growth in rural regions. These plantations are harvested on 5–10 year cycles. For eucalypts, production typically continues over one or two coppice cycles before replanting. Acacia is not managed as a coppice. These plantation resources have been labelled as 'fast-wood forests' (Cossalter and Pye-Smith 2003) without specifying a growth rate that would separate fast- and slow-growing plantations.

Plantation forests are commonly described as 'even aged', but within an estate, only a proportion of the estate would be harvested and replanted annually. This gives rise to a matrix of stands belonging to, for example, 10 age classes—including recently clear-cut stands if stands are harvested on a 10-year cycle. Stands of different age classes would be located discontinuously throughout the landscape. The longer the rotation cycle, the greater the number of age classes and vice versa. In modern forestry, significant proportions of the landscape within the planted estate are conserved for fostering ecological values, including protection and restoration of natural vegetation and riparian zones. For some companies in South America and in parts of SE Asia, protected land represents large areas of about 30% or more of the total land area. Elsewhere in SE Asia, significant proportions of the landscape in major plantation regions are devoted to other land uses such as agricultural and horticultural production and small-scale industry. So plantation forestry and landscape diversity can and do coexist. What is important is proper design and management of the plantations, recognising their roles and values in multifunctional landscapes (Nambiar and Sands 2013; Sands 2013).

Some argue that short-rotation forestry involving large-scale planting with a single species (described as monoculture) will inherently face high risks. There is no evidence to back this assumption as a global case (Powers 1999; Nambiar and Sands 2013). There are several successful plantation ventures in warm temperate regions with one species (e.g. *Pinus radiata* plantations in Australia, New Zealand and Chile), and with short-rotation eucalypt plantations over several decades in tropical and subtropical countries such as Brazil and South Africa. However, the recent experience with disease outbreaks in *Acacia mangium* plantations in Indonesia suggests the need for caution in the future.

Conditions that pose risks to short-rotation forestry include:

- poor matching of species and site
- inadequate recognition of biological risks, especially diseases and pests (Section 3.5)
- inter-annual variation in climate (e.g. prolonged drought or cold in some years)
- management practices resulting in site degradation (Sections 3.2–3.4), adverse environmental impacts, and over-cutting the stands on shorter and shorter rotation cycles.

Well-planned and well-managed short-rotation forestry allow opportunities to:

- manage in an intensive but integrated way to achieve high rates of production enabling faster returns from investments, especially for small growers
- change germplasm at short intervals in the event of pest and disease outbreaks or changing wood markets
- improve wood quality to match processing and product requirements
- spatially redesign forest management units to protect or expand areas dedicated to conservation if needed, and/or enhance other ecosystem values such as water yield
- be more flexible in reallocating plantation land to other land uses.

Climate change poses special challenges to forestry. Short rotations increase flexibility by enabling more frequent replanting with germplasm bred for changing climatic conditions, allied with judicious system management to meet productivity and environmental goals.

2.3 Site and species: determinants of productivity

The concept of site is central to most management decisions and it provides the guiding tool for assessing sustainable wood production. A useful definition of site (modified from West 2006) is an area of land that, if managed uniformly, will produce a more-or-less uniform wood yield across it, within a prescribed time (rotation length), from a particular forest plantation species. Following on from West (2006), site productivity is the total stand biomass (above and below ground) produced, up to any particular age of stand development, of a plantation managed on a particular site when it fully uses the resources available for growth at that site. Measures of productivity include gross or net primary production, net carbon stored or stem wood produced, depending on the purpose for which the information is intended. These measures are all highly interrelated and all of them may be important in research aimed at ecosystem processes and functions. Allocation of biomass to different components, especially to roots which are the major source of soil carbon, in a stand depends on the nutrients and water available at that site, as well as the chosen species and management. For a full understanding of site productivity, one must measure both above- and below-ground biomass but, because of the difficulty in measuring root biomass and turnover, most studies are confined to above-ground components or simply stem wood volume. In this review, for discussion on productivity we use growth rates of stem wood volume (mean annual increment, MAI, in $m^3\ ha^{-1}\ y^{-1}$) and net volume or mass of wood harvested from commercial plantations.

There are well-developed methods for assessing site productivity and classifying the land in management units in relation to productive capacity (ranging from high to low or unsuitable). For such a classification, managers use Site Index (SI) or Site Quality (SQ), which are indices representing and relating to stand-level productivity. Reliable measures of past and current production, and estimates of biophysically meaningful future trends in growth rates for all parts of the estate, are critical for sound planning of harvesting and planting, rotation length, age class distribution and the implementation of sustainable management (O'Hehir and Nambiar 2010; Nambiar and Sands 2013).

The amounts of wood in a stand are commonly measured and reported as total volume of stem wood or merchantable wood (above a certain minimum diameter at the top of the stem) or wood mass that can be processed to products. The proportion of wood recovered for processing depends on the log quality, the product (e.g. pulp, structural timber, engineered wood products, poles or charcoal) and the processing technology. In some cases (e.g. for bioenergy), total biomass (including whole trees and root stumps) is harvested.

The contrasting effects of sites on the productivity of *Eucalyptus globulus* in Western Australia is shown in Table 2, as an example. These sites, located in a Mediterranean climate, had been under pasture for a long time. Growth rates varied more than four-fold between the stands over two rotations, largely determined by available water and nutrients in the soil. The first-rotation stands were in a commercial operation. The second rotations were experimental plantings. Despite this difference in management, the effects of sites on wood production remained dominant. Soil properties determine much of the growth response to management (including nutrient application) and the capacity of the site to maintain productivity through successive rotations.

Impacts of sites and species on productivity are also profound in tropical environments. In a study in the warm, humid and monsoonal environment in Kerala, south India, productivity of experimental plantations across four sites (planted with genetically improved planting stock, with weeds controlled and additional nutrients applied) varied more than four-fold, determined by species and site attribute (Table 3). At Dongmen Forest Farm in Guangxi Province, southern China, a number of trials tested nine eucalypt species and one interspecific hybrid, with and without fertiliser application. Wood volume production of the different species for that subregion ranged from 10.2 $m^3 ha^{-1} y^{-1}$ (for *E. citriodora*) to 24 $m^3 ha^{-1} y^{-1}$ (for *E. urophylla*)(Simpson et al. 2003).

Table 2. Wood volumes from *Eucalyptus globulus* plantations at two contrasting ex-pasture sites over two rotations in Western Australia

	Red earth High fertility	Grey sand Low fertility
Rainfall (mm y^{-1})	1,028	825
Pan evaporation (mm y^{-1})	1,091	1,143
Soil (0–10 cm)		
Total soil organic carbon (g kg^{-1})	49.8	27.7
Total N (g kg^{-1})	2.3	1.4
Bray P (mg kg^{-1})	0.19	0.06
Wood volume		
First rotation—age 8 y ($m^3 ha^{-1}$)	366	96
Second rotation—age 10 y ($m^3 ha^{-1}$)	324	70

Source: Mendham et al. 2008; D. Mendham pers. comm.

Table 3. Wood volumes from two eucalypt species at harvest, age 6.5 years, in short-rotation plantations grown at contrasting sites in a tropical, monsoonal environment, Kerala, south-west India

Species	Soil	Altitude (m)	Rainfall (mm y^{-1})	Volume ($m^3 ha^{-1}$)
E. tereticornis	Sandy loam to clay loam	150	2,000	87
E. tereticornis	Light to medium clay	120	2,700	111
E. grandis	Medium clay to sandy loam	1,280	3,000	190
E. grandis	Clay loam to medium clay	1,800	1,800	360

Source: Sankaran et al. (2008)

All forest sites experience growth-limiting stresses, some of which are universal. For example, all plantation forest sites suffer moderate to severe loss or failure in growth if competition from weeds is not controlled, at least in part. The control of competing weeds is an assured way to increase the share of soil water and nutrients available to planted trees, and may also increase access to light (depending on the canopy development of the competing plants). Management of the diverse stress-inducing factors is essential for realising the growth potential of a species at a site.

An example of how multiple stresses influence the early growth of eucalypts is reported in Table 4.

At this site, control of weed competition (by applying herbicide) and control of defoliation by insects (by applying insecticide) increased the growth of both species by about the same magnitude over their respective controls (15–18 times), despite the large difference in potential growth rates of the two species. *Eucalyptus camaldulensis*, which has a higher degree of drought tolerance, did not benefit from weed control alone, but did benefit from insect control alone because, in the absence of weeds, leaf-foraging insects preferentially targeted this species. *Eucalyptus globulus*, which is very sensitive to water deficits, grew six times faster when weeds alone were controlled but had no benefit from insect control alone. Both species benefited greatly when the competition from both weeds and defoliating insects was managed. The growth effects in Table 4 were largely explained by the response of leaf area to one or more of the stress factors imposed (Nambiar 1990). Defoliation by insects can decimate a plantation.

The discussion above shows how site characteristics—including the biological stresses acting at a site, and the choice of species—have profound influences on productivity.

Table 4. Above-ground biomass of 2-year-old eucalypts planted in a Mediterranean environment in Mount Gambier, South Australia

Management	Biomass (kg ha $^{-1}$)	
	E. globulus	*E. camaldulensis*
Control	946	236
Insecticide applied	990	544
Weed controlled	6,463	180
Insecticide + weed control	14,576	4,214

Source: Nambiar (1990)

3 Biophysical determinants and management of production

The principles and the state of science relevant to the development and application of integrated management for increasing and sustaining productivity are reviewed in this chapter.

3.1 Genetic improvement

This section provides a summary of the key advances made in species selection and breeding in SE Asia and suggests the priorities for future breeding in relation to the emerging risks. It urges a more rigorous evaluation of the impacts of genetically improved planting stock on productivity in operational forestry.

Choice of species

The first step in securing sustainable production is to ensure that a correct choice is made of species, or interspecific hybrid varieties, that are well suited to the plantation environment and the intended use of wood.

Climatic information provides an initial set of criteria for matching the species with the site. The information commonly used includes mean values of annual temperature, maximum temperatures of the hottest month, minimum temperatures of the coldest month, annual rainfall, and length of the dry season (consecutive months with mean monthly rainfall less than 40 mm). The acceptable ranges of these parameters for good plantation growth are determined from the climates of the natural range of the species, together with those of the locations in which the species has grown well in trials or plantations. Areas with climates suitable for the species within a region or larger scales can then be mapped using interpolation techniques (Jovanovic et al. 2000). Table 5 shows the climatic ranges for two eucalypt species, *E. dunnii*, and *E. pellita,* determined in this way. *Eucalyptus dunnii* is suited to subtropical climates and grows well in the highlands of southern China (Jovanovic et al. 2000), while *E. pellita* is suited to hotter, wetter tropical climates such as low-elevation sites in Sumatra and southern Vietnam (Harwood 2008). Projected changes in climate and ambient temperature may influence the planting domains of species (Booth 2013).

Plantations can fail as a result of climatic extremes. For example, the tropical acacias do not tolerate frost, or prolonged exposure to cold temperatures just above freezing. Thus, 10,000 hectares of *A. mangium* and *A. crassicarpa* in southern Guangxi province, China, were destroyed by a cold spell in the winter of 2008. While *E. urophylla* × *E. grandis* eucalypt hybrid clones were also damaged by cold, they have greater tolerance to cold and were used to replace acacia.

Table 5. Climatic ranges suitable for planting *Eucalyptus dunnii* and *E. pellita*

Climatic parameter	Suitable range	
	E. dunnii	*E. pellita*
Mean annual rainfall (mm)	845–1,950	1,200–3,000
Dry season length (consecutive months with mean monthly rainfall less than 40 mm)	0–5	1–5
Mean daily maximum temperature of hottest month (°C)	24–33	24–38
Mean daily minimum temperature of coldest month (°C)	–0.5–17	10–19
Mean annual temperature (°C)	14–22	19–29

Source: *E. dunnii* (Jovanovic et al. 2000); *E. pellita* (Harwood 2008)

Species planted beyond their suitable climatic range may be more prone to disease. *Eucalyptus camaldulensis,* which in its natural range receives rainfall below 1,250 mm y^{-1} (Doran and Turnbull 1997), was planted in central and southern Vietnam in the 1990s, where rainfall exceeds 2,000 mm y^{-1}. There, it suffered leaf blight diseases such as *Cylindrocladium quinqueseptatum* (Booth et al. 2000) and plantations failed. In this region, *A. mangium* and acacia hybrids are planted now. The coastal areas of Binh Thuan and Ninh Thuan provinces in SE Vietnam, which receive less than 1,400 mm y^{-1} rainfall, are too dry for these acacias (Harwood et al. 2007), but *E. camaldulensis* grows well there, free of leaf blight (Kien et al. 2008).

Acacia and eucalypt species planted commonly in SE Asia can grow on a range of soil types; however, there are some specific differences. *Acacia crassicarpa* grows faster on sandy, seasonally waterlogged soils than do *A. auriculiformis* and *A. mangium*. *Eucalyptus camaldulensis* has greater tolerance of seasonal waterlogging and soil salinity than do many other eucalypt species (Doran and Turnbull 1997). (See also Section 4.5.)

Progress in breeding

The current status of breeding is summarised in Table 6. Highlights are as follows.

Three acacias and five eucalypt species, together with some hybrid combinations within both genera, dominate the commercial plantations of SE Asia. Intensive testing of species and provenances confirmed their suitability and good growth, and also identified superior natural provenances for different subregions of SE Asia (for a review of this work in China, see Turnbull 2007).

The importance of provenance selection is illustrated by an example with *A. mangium* in Sumatra (Figure 2). The fastest-growing natural provenance from Papua New Guinea produced 45% greater volume relative to the local Subanjeriji seed source (commonly planted in the first rotation), and 40% over southernmost natural provenances from Tully, Queensland. After the suitable provenances were identified (Figure 2, Harwood and Williams 1991), plantations in SE Asia were established using seed from those provenances, and they also provided the genetic base of subsequent breeding programs. There were similar gains in other species.

Breeding programs follow multitrait improvement objectives that vary from species to species and among organisations. Growth rate has been an important trait for improvement in all cases, together with one or more other traits such as stem and branch form, wood properties and disease resistance. Most of these programs have started with a genetic base using seed families from more than 100 unrelated parent trees from the best natural provenances (Table 6). These were tested in progeny trials, selections from which provided the second generation of the breeding population. Breeding programs for major acacia and eucalypt species have now advanced to the second generation (Table 6), and some have entered the third (Luangviriyasaeng et al. 2010).

Genetically improved seed for planting has been obtained from seed orchards created by thinning the progeny trials, or from clonal seed orchards incorporating the best selections from the trials. However, for some species in some countries (e.g. *A. mangium* and *E. urophylla* in Vietnam), a major proportion of seed for operational planting continues to be collected from natural provenances or from unimproved local plantations.

In eucalypts and acacias, inbreeding (particularly selfing, the extreme of inbreeding) results in loss of vigour of the offspring, regardless of the genetic ranking of the parent tree. Rates of selfing were as high as 50% in natural populations of *E. pellita* (House and Bell 1996). Reduced inbreeding contributed to some of the improvement in growth obtained in the first generation breeding in this species (Brawner et al. 2010). However, light or asynchronous flowering in seed orchards of all acacia and eucalypt species discussed here can result in highly inbred seed, as was shown for *A. mangium* in Vietnam (Harwood et al. 2004). This showed the importance of good seed collection practices to avoid inbred seed.

In addition to improvement in growth, breeding and clonal selection have improved stem straightness, branch size and wood quality. For example, *A. auriculiformis* clones now planted in Vietnam have improved stem straightness as well as vigour, relative to previously planted seed sources (Hai et al. 2008a). Acacia hybrid clones that are commercially planted in Vietnam were selected from many candidates for their superior form and disease resistance as well as for growth rates (Kha 2001).

Table 6. Status of acacia and eucalypt breeding in selected SE Asian countries in 2013

Country	Species	Area of plantations (ha)	Percentage of area clonal	Size of breeding population[a]	Generations of breeding[b]	No. of clones deployed operationally
China	*E. dunnii*	60,000	0	300	1	0
	E. grandis	60,000	80	>300	2	8
	Eucalyptus hybrids[c]	4 M	100	>700[c]	2	20
	E. globulus	120,000	0	200	1	0
Indonesia	*E. pellita*	300,000	80	225	2	20
	A. mangium	500,000	0	660	2	0
	A. crassicarpa	700,000	0	300	2	0
Malaysia	*A. mangium*	250,000	0	200	1–2	0
Thailand	*E. camaldulensis* and hybrids	500,000	>90	300	2	10
Vietnam	*E. urophylla*	200,000	10	140	2	6
	A. auriculiformis	90,000	1	150	2	2
	A. mangium	600,000	0	120	2	0
	Acacia hybrid	400,000	100	–	2	12

[a] Number of unrelated open-pollinated families from above-average provenances
[b] 1 = first-generation progeny trials established, 2 = second-generation progeny trials established
[c] Combinations of *E. grandis*, *E. urophylla*, *E. camaldulensis, E. tereticornis* and *E. pellita*, population size includes all parental species

Evaluating productivity gains from breeding

Differences in performance among genetic treatments in standard breeding trials that use small plots are accentuated because of competitive effects, especially later in the rotation when faster growing ones dominate slow-growing varieties (Stanger et al. 2011). Such trials cannot be used to reliably predict productivity gains in operational plantations and to extrapolate the benefits of breeding. To do this, we require genetic gain trials that compare the new, improved material with relevant controls representing that previously deployed, using large plots to minimise competitive interactions. They need to be conducted on the major site and terrain types, and managed as operational plantations.

Results of one provenance trial from Sumatra and two genetic gain trials from Vietnam are summarised in Table 7. All trials used 49-tree plots and five replicates. Significant increases in plantation productivity were achieved by using superior provenances and first-generation improved seedlots, rather than locally available unimproved seed sources. The provenance trial of *A. mangium* in Sumatra showed a 45% increase in volume from the fastest growing natural provenance relative to an unimproved local seed source (see also Figure 2). Across three genetic gain trials of *A. auriculiformis* (Hai et al. 2008a), conical stem volume at age 4 years averaged 13 m^3 ha^{-1} for a local seed source, 19 m^3 ha^{-1} for a mix of the best natural provenances and 28 m^3 ha^{-1} from select trees in a seed orchard. These seedlots ranked in the same order at three sites in central and northern Vietnam under local management practices. Another trial at Cau Hai in northern Vietnam compared the growth of several *A. mangium* seedlots and acacia hybrid. At age 8 years a seedlot collected from selected trees in a seed orchard was the fastest *A. mangium* source, followed by a seed mix of superior natural provenances, which in turn grew faster than a local commercial seed source. A mix of three production clones of acacia hybrid grew faster than all *A. mangium* sources. Volume growth of acacia hybrid was 138 m^3 ha^{-1}, 89% greater than 73 m^3 ha^{-1} for the commercial *A. mangium* source (N.D. Kien pers. comm. 2013).

The second generation of pure-species breeding has resulted in less improvement in volume. Results from progeny trials of *E. pellita* (Leksono et al. 2008; Brawner et al. 2010), *A. auriculiformis* (Luangviriyasaeng and Pinyopusarerk 2003; Hai et al. 2008a) and *A. mangium* (Arnold and Cuevas 2003; Nirsatmanto et al. 2004) indicate that for these species the second generation of breeding has not given more than 5–10% additional volume gain in trials. This is not surprising, as provenance selection and reduction of inbreeding contributed to the large improvements in growth achieved in the first generation of breeding.

Table 7. Stem volumes over bark for different genetic treatments in trials comparing improved and unimproved genetic stock of acacias

Region and country	Species	Genetic treatments[a]	Assessment age (years)	Wood volume (m^3 ha^{-1})
South Sumatra, Indonesia[a]	*A. mangium*	Local seed source	5.5	172
		Best natural provenance		250
Central and northern Vietnam[b]	*A. auriculiformis*	Local seed source	4	13
		Best natural provenance		19
		Best seed orchard seed		28
Northern Vietnam[c]	*A. mangium*	Commercial seed source	8	73
	A. mangium	Best natural provenance		106
	A. mangium	Seed orchard		124
	Acacia hybrid	Mix of hybrid clones		138

[a] E.B. Hardiyanto pers. comm. 2013. Volume over bark estimated from height, diameter and form factor.
[b] Hai et al. (2008a). Mean of three trials in central and northern Vietnam. Conical tree volumes, calculated from height and diameter at breast height.
[c] N.D. Kien pers. comm. 2012. One trial in northern Vietnam. Volume over bark estimated from height, diameter and form factor.

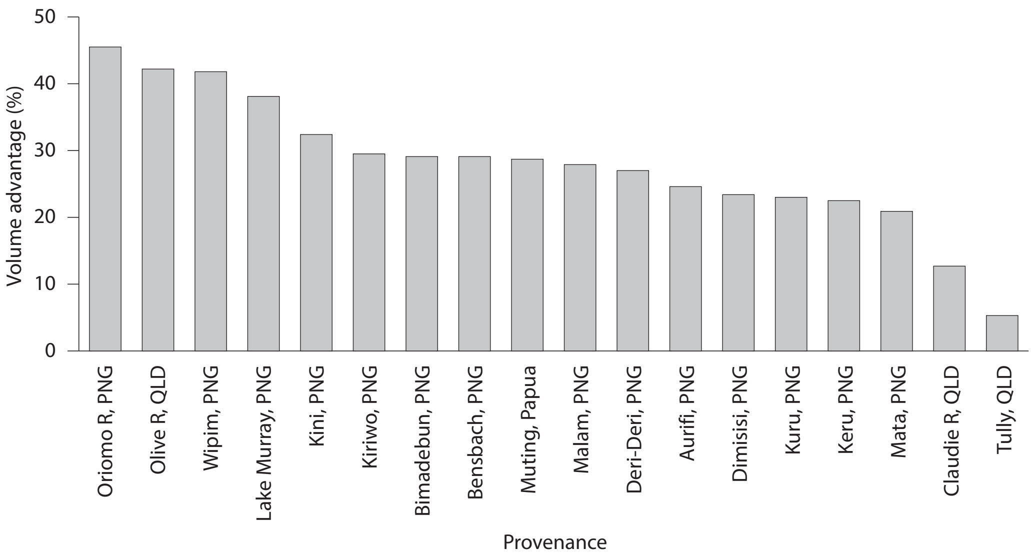

Figure 2. Stem volumes of *Acacia mangium* provenances compared with an unimproved local seed source (Subanjeriji) at 5.5 years in a trial in southern Sumatra, Indonesia (E.B. Hardiyanto pers. comm. 2013). PNG = Papua New Guinea, QLD = Queensland, R = River

Clonal forestry

Clonal forestry enables planting of selected genotypes to capture non-additive and additive genetic gain, whereas use of open-pollinated seed from a seed orchard can capture only additive gain (White et al. 2007). It also facilitates the use of interspecific hybrids. It has the potential to provide uniformity in tree size, stem form and wood properties. However, overall plantation uniformity depends on site conditions and management. This is illustrated by the high spatial variability in growth rates found in clonal plantations examined in this study (Chapter 5).

Over half of the total plantation area under review in this report is clonal (Table 6). However, some broadly planted species including *A. crassicarpa*, *A. mangium* and *E. dunnii* are not amenable to clonal forestry.

Clones of *A. auriculiformis* (Hai et al. 2008b), *E. camaldulensis* (Kien et al. 2008), *E. pellita* (Brawner et al. 2010) and *E. urophylla* (Kha et al. 2003) have been developed. However, where the environment is well suited to a pure species, use of improved seed produces improved planting material more quickly than does clonal forestry. Seeds from seed orchards displayed similar growth rates to selected clones in an *A. auriculiformis* trial in Vietnam (Hai et al. 2008a). In South Africa, growers of *E. grandis* are reverting from clones to improved seed because of the good growth and lower costs of seed (R. Griffin pers. comm. 2013).

If the choice is to use seed, genetic gain via seed orchards can be increased by progeny-testing the parent trees and collecting seeds only from superior parents. Clonal multiplication of seedlings of these seed families (without subsequent testing of individual clones) is now being used to mass-propagate selected *A. crassicarpa* and *A. mangium* families in Sumatra, Indonesia (Wong Chin Yong pers. comm. 2013).

Interspecific hybrids

As can be seen from Table 6, interspecific hybrids dominate the eucalypt plantations of China and are important in Thailand, while acacia hybrids are important in Vietnam. They must be planted as clones, not as seeds.

Interspecific hybrids can combine complementary traits of the parents. An example is the *E. grandis* × *urophylla* hybrid, which combines the disease resistance and higher wood density of *E. urophylla* and the higher growth potential of *E. grandis* (Assis 2000). Some interspecific hybrid combinations grow faster than either parent species.

In a control-pollinated breeding program in Brazil, involving crossing among *E. camaldulensis*, *E. grandis*, *E. pellita* and *E. urophylla* and their hybrids, the best of the interspecific hybrid families grew faster to age 7 years than did the pure-species families (Assis 2000). Similarly, in northern Vietnam, faster growth of hybrid combinations among *E. camaldulensis*, *E. exserta* and *E. urophylla* over pure-species crosses involving the same parent trees was reported by Kha et al. (2003). In each of six clone trials in southern China, clones of pure species had markedly inferior growth compared with the fastest-growing interspecific hybrid clones including the same taxa (R. Arnold pers. comm. 2013).

Faster growth of acacia hybrid clones over seedlings of the two parent species was demonstrated in a trial at Ba Vi, northern Vietnam. At age 4 years, mean annual height increment was 2.9 m for hybrid clones, compared with 2.2 m for *A. mangium* seedlings and 1.5 m for *A. auriculiformis* seedlings. Table 7 and Kha (2001) report other trials in which this hybrid grew faster than the parent species. However, in one trial in southern Vietnam, genetically improved seedlots of *A. mangium* grew at rates similar to acacia hybrid clones (Kha et al. 2012).

Breeding for the future

As shown in Table 7, improved varieties of the acacia and eucalypt species and hybrids can increase productivity when planted at appropriate sites and managed well. However, diseases and pests pose severe risks to production (Section 3.5). This calls for a revision of breeding objectives. Future breeding should give very high weighting to genetic improvement in traits such as disease resistance that reduce risks to sustainable production, rather than focusing primarily on attempting to deliver further major increase in growth rates and ever-shorter rotations.

Breeding to improve resistance to diseases and pests can involve (i) selection within species or (ii) interspecific hybridisation. Changing to a more resistant species is another option.

The planting of clones resistant to disease and pests can assist in sustaining productivity (Dehon et al. 2013). In a study in Brazil in which 23 clones of *E. pellita* from a range of provenances were inoculated with three major fungal pathogens, 12 clones were resistant to *Puccinia psidii* (eucalypt rust), 16 to *Ceratocystis* stem wilt and 12 to *Cylindrocladium* leaf blight, and three to all three diseases (Guimaraes et al. 2010). Similarly, there are differences in susceptibility to *Ceratocystis* stem wilt/canker among eucalypt hybrid clones in southern China (Chen et al. 2013). In Sumatra, Indonesia, where *Ganoderma* root rot disease causes serious mortality in *E. pellita* plantations, use of disease-resistant clones of *E. pellita* offers promise of improving productivity (E.E. Wirawan pers. comm. 2013).

Eucalyptus pellita is resistant to a range of tropical diseases (Harwood et al. 1997; Harwood 2008). It can be hybridised with other less-resistant species in the eucalypt subgenus *Symphyomyrtus* such as *E. camaldulensis*, *E. dunnii*, *E. grandis*, *E. tereticornis* and *E. urophylla.* This offers the prospect of incorporating resistance to disease in multi-species hybrid combinations, along with other favourable characteristics from the other parent species, including vigour, adaptation to drier or cooler climates (Table 5), and improved wood properties. Such a multi-species hybrid breeding approach has been implemented in Brazil (Resende and Assis 2008). Pathogens can evolve rapidly, attacking previously resistant eucalypt genotypes (Graca et al. 2011). Thus it is essential to maintain ongoing selection and breeding, based on genetically diverse populations of the parental species.

Acacia mangium and *A. crassicarpa* are highly susceptible to *Ganoderma* root rot and *Ceratocystis* stem wilt/canker. These pathogens have caused major losses in wood production and a reduction in the area planted to *A. mangium* in Sumatra (Section 4.1). Initial indications are that there appears to be little genetic variation within *A. mangium* in susceptibility to root rot (Eyles et al. 2008) or *Ceratocystis* (J. Brawner pers. comm. 2013). The level of genetic diversity in this species is exceptionally low, compared with other forest trees (Moran et al. 1989). No acacia species with superior disease resistance are available for planting or hybridisation with *A. mangium*. Therefore growers are switching to *E. pellita.*

There are differences in susceptibility to the eucalypt gall wasp among eucalypt species, provenances, interspecific hybrids and individual clones (Dittrich-Schroder et al. 2012; Chang et al. 2012; Luo et al. 2013). In Vietnam, *E. camaldulensis*, *E. grandis* and *E. tereticornis* were the most susceptible of 18 eucalypt species tested; 65–90% of seedlings showed symptoms of *Leptocybe* attack in the nursery. Only 12–24% of *E. urophylla* and *E. pellita* seedlings were affected. Similar rankings in susceptibility were evident on saplings in field trials in northern Vietnam (Pham et al. 2009).

In Brazil, before large-scale release, clones are systematically screened for resistance to major diseases by inoculating young trees with the diseases and monitoring their tolerance to infection under controlled conditions and in the field (Dehon et al. 2013). Systematic screening is strongly recommended for acacia and eucalypt breeding in SE Asia, given the increasing problems from diseases (Section 3.5).

The current genetic diversity of clonal plantations of both acacias and eucalypts in SE Asia is low; some growers plant only two or three clones across the entire estate. In such cases, onset and spread of serious disease or pest attack can be rapid. Unless supported by an ongoing breeding and clonal testing program, clonal plantations represent a genetic dead end with no capacity to adapt to changing environments. Growers should increase the numbers of clones they plant.

In Brazil, companies plant 5–10 production clones in any 1 year (Dehon et al. 2013). They aim for about half of these to provide 70–80% of the planting stock in any year, and to replace these dominant clones with two to five new ones every 3–4 years. To achieve this, hundreds of candidate clones from breeding programs are evaluated regularly. This scale of activity can be managed only by large companies, breeding cooperatives or major research agencies. Dehon et al. (2013) stress the importance of breeders and operational managers working together in evaluating pilot-scale plantations of new clones. National-level cooperatives such as the China Eucalypt Breeding Alliance have obvious advantages and this approach deserves consideration elsewhere.

Ongoing pure-species breeding and maintenance of a wide genetic base are the basis for development of new interspecific hybrid varieties. It is important that breeding programs retain the genetic diversity of the original base populations, because it may be necessary to access genetic variability to breed for emerging risks or to cater for new market requirements. This does not involve the retention of the original base-population plantings over successive decades, which would be impractical; rather, comprehensive seed collections from all the introduced provenances can be stored securely for possible future use.

Clones developed in one region should not be planted in commercial scale outside that environment without rigorous testing in the new region. For example, clones of the *E. urophylla* × *grandis* hybrid, developed in subtropical southern China, have failed in equatorial environments of Sumatra and Borneo, because of their susceptibility to fungal leaf blight diseases. Similarly, *E. pellita* clones developed in Indonesia or Malaysia would be unlikely to succeed in coastal southern China (Luo et al. 2006).

Productivity of a stand at the end of a rotation is determined by multiple factors. While genetic potential of the planting stock is very important, soil and site attributes in the landscape vary significantly, and there is considerable variation in management. These other factors also strongly influence productivity.

Key questions for the future include: How is the genetic potential expressed under such operational realities? Does the validation of improved genetic material take into account such operational realities and restrictions? Few results from genetic gain trials are available for acacias and eucalypts in SE Asia. It is necessary to establish ongoing evaluation of improved genetic material covering the spatial variability and management across the estate to benchmark progress in breeding and justify ongoing investments in relevant R&D.

3.2 Managing productivity

Sustaining wood production over the long term

The productive capacity of a site is not an immutable reference point or an unchanging base line; it is a snapshot in time because site productive capacity can be upgraded by good management or downgraded by poor management (Nambiar 1999). Results from studies on long-term productivity trace trends in production back to factors including the choice of species and quality of germplasm, soil and site management practices and overall quality of the management adopted by the enterprise (Powers 1999; Evans 2005; O'Hehir and Nambiar 2010; Nambiar and Sands 2013). The management goals for the plantation can also affect total production; plantations managed to produce small-diameter commercial logs on short clear-fall rotations and those managed to produce large-diameter sawlogs over long rotations via thinning regimes will have different net productivity outcomes (West 2006). Acacia and eucalypt plantations in SE Asia are overwhelmingly managed for the former objective (Chapter 1).

The impacts of management on production over three successive rotations and over a century of *Pinus radiata* plantations in South Australia are described by O'Hehir and Nambiar (2010). They showed productivity changes at plot, compartment and regional levels. Changes at the compartment level are illustrated in Figure 3. Here, the widely known 'second-rotation decline' in productivity became apparent in the 1960s. Research showed that the causes of this can be attributed mainly to the postharvest loss of organic matter and nutrients caused by high-intensity burning of biomass lying across the site or heaped or gathered into windrows, an operation that often carries some surface soil along with the slash and litter. This operation was followed by ploughing for weed control, which caused further loss of soil organic matter. It also accelerated mineralisation and leaching losses in autumn–winter when seedlings were planted for the next rotation. For the third rotation, management employed a research-based

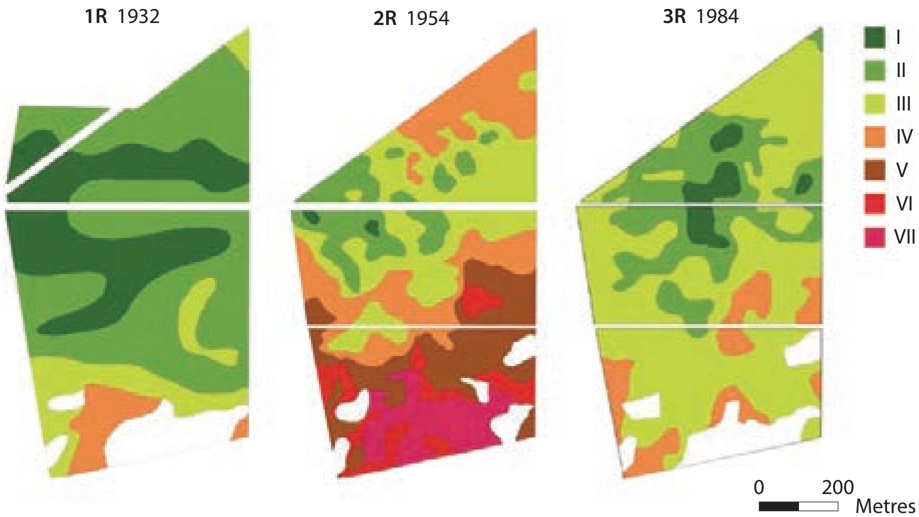

Figure 3. Productivity of three rotations of *Pinus radiata* in South Australia (O'Hehir and Nambiar 2010)

package of practices including conservation of site organic matter and nutrients, minimum cultivation, ongoing genetic improvement in planting material, judicious weed control, replacing ploughing with herbicides, fertiliser use and stand management to hasten the growth of the young stand. This underpinned large-scale improvements of site quality and higher productivity in second- and third-rotation stands across the region (Nambiar 1999; O'Hehir and Nambiar 2010).

The numbers in Figure 3 are years of planting. Changes in productivity at the compartment (management unit) level are represented by Site Quality (SQ) on a scale of I (highest) to VII (lowest) for three successive rotations (R). Productivity declined from the first to the second rotation but improved in the third rotation.

Even when forests are managed on rotation cycles in decades, management of the inter-rotation phase is critical for sustainability (Nambiar 1996; Brandtberg and Olsson 2012; Ponder et al. 2012; Wall 2012). This is even more so for short-rotation forestry (Nambiar and Brown 1997; Gonçalves et al. 2008b).

Inter-rotation management

When plantations are managed on rotations ranging from 25–35 years (e.g. teak plantations in the tropics), stands are thinned to harvest logs two or more times during the rotation, and then clearfelled. Thinning is a mild level of disturbance. It opens up the canopy, and fallen crowns (slash) are left in situ to aid retention of organic matter and nutrient cycling. A thinned stand will rebuild its canopy, as trees grow at rates faster than they did during the pre-thinning stage because they have more site resources available per tree. Thus, the plantation receives major disturbance only every 25–30 years at final harvest. In contrast, short-rotation acacia and eucalypt plantations are clearfelled on rotations of 5–10 years. All commercial wood and, in some cases, the total biomass is removed, followed by disturbing or damaging site preparation practices for the next crop. Unlike long-rotation forestry in which there are sequential opportunities for improving production through later-age stand management, options for interventions beyond the establishment phase in short rotations are very limited. Thus, the management decisions implemented during the inter-rotation phase are critical for subsequent production.

The processes governing sustainable wood production in plantation forests in subtropical and tropical environments and the impacts of management on them were synthesised in a multidisciplinary book (Nambiar and Brown 1997) that summarised some key principles of management:

- First, plantation management operations should ensure that the soil base is protected and disruptions to ecological processes (carbon, nutrients and water cycles) are held within known boundaries of resilience to support long-term productivity.
- Second, avoiding extreme soil perturbations, conserving site organic matter pools, and due accounting and management of nutrient inputs and exports will enable adequate nutrient-cycling processes within the ecosystem.
- Third, for plantation forestry in the tropics, the period of inter-rotation management is a window of high risk to the site but also a time of opportunity to correct past mistakes and set the course for sustainable management.
- Furthermore, scientifically based management that aims to achieve sustainable production is also the best way to minimise or avoid environmental impacts within and beyond the plantation estate.

In the following sections we discuss how different management practices deployed during the inter-rotation phase impact on key processes that drive productivity.

Harvesting operations and their impacts on site management

The inter-rotation phase starts with harvesting a stand. Clear-cutting is a major perturbation event. Impacts may be directly related to the logging practices, the nature of the terrain, the intensity of biomass removal, and the level of disturbance and loss of soil. Methods of harvesting and hauling logs to the log dump or road may be fully mechanical, a combination of mechanical and manual, or simply manual. All these systems are practised in SE Asia. Ilstedt et al. (2004) evaluated the impacts of crawler tractor harvesting of *A. mangium* plantations on soils and growth of the next rotation to age 2–3 years. They compared selected soil properties in plots established on harvesting tracks and outside the tracks, superimposed with various rehabilitation treatments including fertiliser addition and soil tilling. At age 2 years, growth of trees outside the tracks was 60% higher than on unimproved tracks, but overall improvements in growth were much greater with fertiliser application. Soil porosity was lower on tracks than outside them, and this apparently gave rise to differences in short-term soil water retention and availability. Given some of the confounding aspects (e.g. higher mortality outside the track due to late planting of that treatment) and the short-term nature of the study, these results are indicative only.

Clearfelling and log-extraction practices can influence plantation productivity. This is generally thought to be due mainly to soil compaction and loss and displacement of surface organic matter (e.g. Powers 2006). However, elaborate and multisite network studies across the USA and Canada have not found a consistent effect of compaction per se (even when the entire experimental plots were deliberately compacted) on plantation productivity at age 10 years among the common species planted in those countries (Ponder et al. 2012). Harvesting would not lead to uniform compaction throughout the area (as in the study above); compaction occurs along machine paths and snig tracks. So studies are typically confined to replanted trees growing on patches or rows subjected to various degrees of disturbance. Studies in South Africa have found that the effects of compaction on the growth of eucalypts depend strongly on soils: volume reduction in compacted areas compared with non-compacted areas ranged from 25% to 2% depending on soil types. Impacts of deployment of forwarders, loggers, tractors and extraction/snig tracks varied depending on terrain and soils (du Toit et al. 2010). In general, effects of machinery-imposed compaction on soil properties (such as bulk density, strength, porosity and water-holding capacity) have been more demonstrable than effects on long-term stand growth.

Studies with eucalypts in South Africa also showed that, under conditions prevailing in that environment, practices such as ripping and sub-soiling gave erratic results—effectiveness (if any) being highly dependent on soil type, soil water availability and design of the cultivation implements. Such operations carried out up and down the slope (not along the contour) may do more harm than good. Retaining organic matter during harvest operations and ensuring that harvesting machines traffic only over the logging slash are the best ways to avoid both soil damage and the need for ameliorations such as ripping, which are expensive and provide uneven outcomes. The natural bulk density of soils varies greatly. Tree growth in some soils can benefit from ripping, which assists root growth, if it is done with due consideration of the terrain, soil type and the operating season (Gonçalves et al. 2008a).

The uncertain effects of harvesting-induced soil compaction on productivity of the next crop (Smith et al. 2001; Ilstedt et al. 2004; Ponder et al. 2012) are in contrast to the effects of the postharvest management of site biomass—loss of which almost universally led to decline in production in subtropical and tropical plantations of eucalypts, acacia and hybrid pines (Nambiar and Kallio 2008; also see Section 3.4). Mechanical harvesting of short-rotation plantations in terrains that are flat or moderately steep can be done with little damage to sites if slash and litter are retained, and if harvesting is not done when soils are wet (see Photo 5). A key requirement is to develop systems that minimise machine movements across the site. Proper harvesting codes facilitate site-based decisions. Practices causing displacement, loss of site organic matter, erosion and unacceptable levels of soil compaction will damage future production, as will the burning of slash (see Photo 29). A good harvesting practice should conserve site resources and facilitate subsequent site preparation and planting. Site preparation should not be seen as a way to repair harvesting damage.

Biomass displacement and removal

As seedlings grow to a stand of trees, they progressively accumulate biomass in standing trees, roots and litter, within which nutrients are tightly cycled through biogeochemical pathways including internal re-translocation and reuse for new growth. Nutrients also accumulate and partly immobilise in litter, duff and soil organic matter. Clearfelling disrupts this cycle, opening up the site and triggering major changes to the microclimate.

Export of biomass from the site involves a range of intensities, from merchantable wood only with debarking on site, through to removal of all above-ground biomass and stumps. After harvest, if organic matter (slash biomass) is burned or displaced (e.g. by windrowing), soil losses are unavoidable and nutrient cycles are severely disrupted. The shorter the rotation, the greater will be the intensity of export and the degree of perturbation (Folster and Khanna 1997; Mackensen and Folster 1999).

In order to understand the fate of above-ground biomass during the postharvest operations, it is useful to examine the amounts and distribution of biomass. There are many accounts of this in the literature, and an illustrative summary is given in Tables 8 and 9.

Table 8. The range of above-ground biomass (excluding litter) of commonly planted species in short-rotation forestry. Revised from Yamada et al. (2004)

Species	Regions	Age (years)	Above-ground biomass (dry t ha^{-1})
Acacia auriculiformis	Southern Vietnam	6–7	96–136
A. mangium	Indonesia, Papua New Guinea	6–9	109–190
Eucalyptus globulus	Australia, Chile	6–8	69–275
E. grandis	Brazil, India, South Africa	7–12	140–324
E. camaldulensis	Thailand	6–15	79–95

Table 9. Nutrient contents and distribution in selected acacia and eucalypt short-rotation plantations of near-harvest age

		A. auriculiformis[a] Vietnam	*A. mangium*[b] Indonesia	*E. globulus*[b] Australia	*E. grandis*[c] S. Africa	*E. tereticornis*[d] India
Stand age		6	6	13	7	7
AGB (t ha^{-1})	Bark	8.0	14.2	26.9	12.8	17.9
	Stem	76.6	124.7	186.9	107.4	46.8
	AGB	107.5	189.5	256.9	133.8	64.8
N (kg ha^{-1})	Bark	116.5	139.0	51.1	42.6	32.5
	Stem	136.5	236.0	114.0	77.3	74.6
	AGB	475.2	661.0	465.8	249.2	178.6
P (kg ha^{-1})	Bark	8.1	1.5	3.4	6.3	11.0
	Stem	47.7	7.8	49.0	4.1	20.7
	AGB	76.8	14.3	68.7	17.8	42.4
K (kg ha^{-1})	Bark	38.7	35.6	50.6	52.9	70.7
	Stem	116.4	37.4	104.7	81.6	90.3
	AGB	231.5	191.2	309.5	189.0	229.9
Ca (kg ha^{-1})	Bark	24.4	163.7	582.9	101.0	170.8
	Stem	15.9	103.5	214.9	80.8	91.2
	AGB	67.1	415.8	1,167.5	248.1	409.1

Source: [a] Vu Dinh Huong pers. comm.; [b] Yamada et al. 2004; [c] du Toit et al. 2004; [d] Sankaran 1999
AGB = above-ground biomass

The amounts of above-ground biomass accumulated before harvest vary widely according to species, site and rotation length. In general, there will be a close relationship between stem diameter or wood volume and stem wood mass. But the relationship between wood volume, which is cumulative, and the mass of other components of biomass—leaves, bark and small branches—will be more variable. These other components are non-cumulative on trees as they have shorter longevity and senesce and fall to become litter. Litter decomposes and hence loses mass. Non-cumulative components of the biomass can be accounted for by measurements, including collecting and measuring litter fall, at regular intervals.

Management decisions about whether to harvest wood alone or whole trees, and how they are harvested, will affect nutrient pools. Data in Table 9 show how biomass and nutrients are distributed in stands near harvest age, which allows estimation of net export in relation to the intensity of harvest.

The amount of wood biomass as a proportion of the total above-ground biomass ranged from 66% to 89% but contained much lower proportions of the nutrient elements. In contrast, bark mass at harvest was 10% or less of above-ground biomass (except for *E. tereticornis* where it was 28%), but contained much higher proportions of all nutrients. For example, in *E. globulus*, bark accounted for only 10% of the mass but contained 50% of calcium (Ca) and in two acacia plantations bark accounted for 7% of the mass but 36–39% of the Ca (Table 9). More details of biomass and nutrients for a range of plantations can be found in Nambiar and Kellio (2008).

When whole trees are harvested, the entire live biomass is removed from a site. Furthermore when trees are processed near landings (roads) several fallen trees are gathered, gripped and dragged as a bundle, and litter is displaced or carried entangled in the crown to the landing. After recovering the merchantable wood, slash is piled at the landing where it may be left, sold off or unevenly redistributed back to the plantation. The increases in nutrient removal from whole-tree harvest are two- to fourfold, depending on species, site and nutrient (Table 9). In order to manage the impact of these operations, managers should recognise the potential export of nutrients from sites in relation to growth rates and the capacity of the soil/species combination in question to cope with such levels of depletion.

The progressive increase in the amounts of nutrients removed from sites as a consequence of four intensities of biomass removal from stands of *A. mangium* in Sumatra and *E. grandis* in Brazil is illustrated in Figure 4. Note that some of the nutrient axes in Figure 4 have different scales for the two species. The patterns of export are similar in both cases but the net amounts are different. Amounts of nitrogen (N) removed from the acacia are far higher than those from the eucalypt, in part because tissue N concentrations and leaf canopy mass may be higher as acacias can fix atmospheric N. The amounts of phosphorus (P) removed from the eucalypt are much higher than those from the acacia. As the intensity of biomass removed increased from merchantable wood only (with debarking at the stump) to whole trees, or the extreme case of complete above-ground biomass including litter, depletion of N, P, potassium (K) and Ca progressively increased. This pattern of nutrient depletion as a consequence of the intensity of harvests has been demonstrated in several cases; for example, *A. mangium* in Kalimantan (Mackensen and Folster 1999), *E. urophylla* in China (Xu and Dell 2003), *A. mangium* in Riau Province, Sumatra (Siregar et al. 2008; Siregar pers. comm. 2012), and elsewhere. If harvest also included removal of stumps, further loss from the site would follow.

Debarking at stump (which is feasible and is sometimes done manually or mechanically) is a very desirable practice (Figure 4 and Table 9). Retention and distribution of bark would improve the future supply of nutrients, notably P and Ca in eucalypts and Ca in acacias. Concentrations of nutrients that are mobile within trees decrease as the trees grow older because of internal re-translocation. Therefore wood and bark in young 5–7-year-old stands are richer in nutrients than they are in trees that are 10 or more years old. Small-diameter branches, twigs and litter all have higher nutrient concentrations than commercial wood, and their retention on site is likely to be important for maintaining site nutrient capital. The difference in nutrient content between the species in Figure 4 should not be directly attributed to species per se, except for N. Amounts of minerals including Ca and K accumulated in the biomass depend strongly on supply from the soil. The same species grown on different soils, on adjacent sites, may grow at different rates and accumulate different amounts of biomass and nutrients (Nambiar and Kallio 2008).

Site management for the next rotation

Export of biomass and nutrients in merchantable stem wood is inevitable, but it is not a major cause of site degradation. The critical factor is the manager's decision on how the site will be prepared for replanting. Slash left at the site is sometimes called 'harvest residue', leading to the assumption that it is to be 'cleaned out' to create a smooth planting surface. In fact, slash and litter have irreplaceable roles in the healthy functioning of ecosystem processes (O'Connell and Sankaran 1997). These roles include protecting soil from damage during the operation of heavy machinery, minimising wind and water erosion, and serving as a source of available nutrients.

Burning, depending on the fuel (slash and litter) load, its moisture content and the wind speed, will lead to near complete loss of N in smoke and volatilisation, and partial loss of nutrients including P, Ca and K as particulates. Post-fire ash remaining on the surface can be blown away by wind or be washed away with the onset of rains, especially from exposed and steep slopes (see Photo 29). It is not possible to enumerate the reported loss of nutrients in a range of ecosystems in this review. Site-specific estimates can be readily made from data of the type described in Table 9.

As an example, in eucalypt plantations, the amounts of N in the slash and litter may be between 125 and 500 kg ha^{-1}, depending on the biomass and the productive capacity of soils (Nambiar and Kallio 2008). This pool is highly vulnerable to loss in a matter of days if sites are windrowed or heaped and burned.

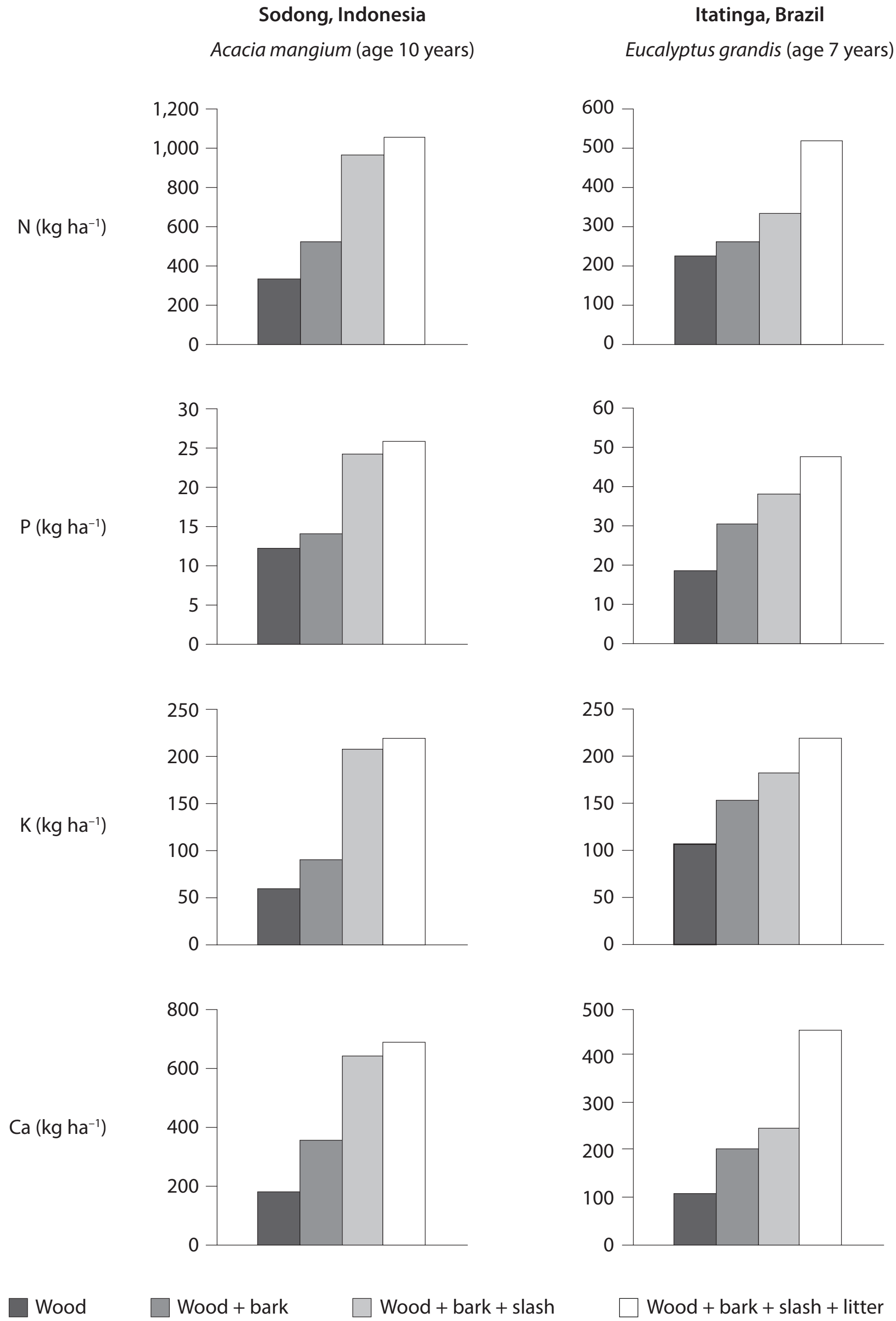

Figure 4. Nutrient export in biomass harvest: two case studies from Sumatra and Brazil (Nambiar and Kallio 2008)

Burning slash and litter, as compared with their complete mechanical removal, may sometimes improve tree growth for a short time (du Toit et al. 2008). This is also seen in Figure 5 stimulated by the ash effect (enriched by concentrations of P and base cations Ca, K and Mg in ash) and higher rates of mineralisation. However, repeated burning and loss of organic matter would degrade sites in the long term (Gonçalves et al. 2007; Laclau et al. 2010; O'Hehir and Nambiar 2010). These practices and losses could be more limiting to production for eucalypts, which do not fix N, as the canopy development of eucalypts is dependent on N supply. Displacement of slash and litter will aggravate not only N deficiency but also P and Ca deficiency in some soils (Gonçalves et al. 2007). The surface 0–5 cm soil horizon holds the highest concentration of soil organic carbon (Figure 6), N, extractable P and exchangeable K, Ca and Mg in plantation soils. Gonçalves et al. (2008) and Smith et al. (2008) give examples. Displacement of even a thin layer of surface soil would have adverse effects on productivity in the long term.

In practice, when the heavy blade mounted on a bulldozer pushes forward the slash (also described as harvest residue) it invariably gathers a significant part of the litter and scalps the soil surface, damaging the soil (see Photos 18, 19). Pulling out stumps will aggravate the problem. Even in forests that are managed on long rotation cycles of several decades in Scandinavian countries, impacts of stump harvesting on the soil and the environment are matters of concern (Persson 2013). If these operations are conducted when the soil is dry, large amounts of fine soil particles (≤ 1 mm fraction) are unearthed, lifted and blown away by wind. If harvesting is done in wet weather, soil compaction and erosion are common outcomes. Several publications examine the consequences of these damaging practices for tropical short-rotation plantation systems (Sim and Nykvist 1991; Panitz and Adzmi 1992; Mackensen et al. 1996; Folster and Khanna 1997; Nambiar and Brown 1997; Persson 2013).

Clearfelling and site-preparation practices (including burning) increase mineralisation in soils. Most parts of SE Asia receive torrential rains in the wet season. When rates of mineralisation are higher than the rates of uptake by trees (and associated vegetation at the site), nutrient leaching can occur if there is water movement. The risk of leaching is moderate to high from harvest and during site preparation and initial seedling growth after planting. However, it is very low or nil once trees reach the sapling stage and if the understorey is allowed to return rather than be completely eliminated, as growing trees and residual understorey serve as sinks to nutrients. If the terrain is steep and exposed to surface run-off following the onset of rains, nutrients and soil may be transported off site with water flow.

A Congo study shows how important proper management of site organic matter after harvest is to the productivity of the next crop (Figure 5).

Treatments in Figure 5, in increasing ascendency from the lowest to the highest in volume, are: all above-ground biomass including litter removed (R); whole-tree harvest (WTH); all slash and litter burned (B); only merchantable wood and bark harvested (TH); wood alone removed, debarked at stump (SWH); slash from WTH added on top of the in situ slash = double slash (DS).

In this second-rotation stand, stem volume was reduced by 44% when all the organic matter (slash and litter) was removed at the start of the second rotation. Productivity increased progressively as the amount of organic matter (and nutrients) retained increased with various management practices. Laclau et al. (2010) also showed a significant linear relationship between the increase in organic matter levels and volume and stem wood production. Plots in which the slash and litter were burned grew more wood compared with those in which all organic matter was removed, partly because of the mineral nutrients supplied from the ash (a common feature at sites that are deficient in P and base cations), but the wood volume was significantly lower than that obtained by retaining the slash. Whole-tree harvesting would therefore substantially reduce growth of the subsequent rotation, compared with the best yield at this site.

Losses of organic matter and nutrients are expected to have more serious consequences on tree growth in sandy soils than in soils with a heavier texture. However, evidence is clear that depletion of site organic matter and associated nutrients lead to loss in production under a wide range of conditions: for example *E. grandis* in Brazil (Gonçalves et al. 2008a); *E. urophylla* in China (Xu et al. 2008); *A. auriculiformis* in South Vietnam (Huong et al. 2008); and *A. mangium* in Sumatra (Hardiyanto and Nambiar 2014).

Depending on the soil type and the species being grown, some nutrient elements will be more limiting than others and it is important to assess the rate and degree of depletion of each nutrient in relation to the reserves, nutrient additions and the capacity of the soil. This is further brought out by the results from a network project in which plantations at a majority of sites showed a reduction in growth rates, in some cases severe, if whole-tree harvesting was practised, even when the litter layer was retained. Conversely, conservation of site resources after wood harvest of the first rotation mostly improved production of the second-rotation crop in eucalypts, acacia, pine and Chinese fir (Nambiar and Kallio 2008). These results have been further confirmed by several experiments in diverse environments and with a range of species (Tiarks et al. 2004; Tutua et al. 2008; Zhiqun et al. 2013; Hardiyanto and Nambiar 2014) and comprehensive reviews (Titshall et al. 2013; Gonçalves et al. 2013). One of two *E. globulus* sites in Western Australia that had high soil fertility (the most productive site in the network, with MAI 46 $m^3\ ha^{-1}\ y^{-1}$ at age 9 years) did not show a decline in production with biomass removal in the first rotation (Nambiar and Kallio 2008). However, biomass removal associated with the second harvest significantly reduced production in the third rotation (D.M. Mendham pers. comm. 2014). A global review of forest harvesting emphasises the risks to soil properties if harvesting and management practices include whole tree harvesting and intense biomass removal even under long rotation cycles (Wall 2012).

There is therefore good evidence to conclude that few, if any, subtropical and tropical plantation forests would be able to cope with practices that heavily deplete or displace site organic matter and nutrients and damage soil every 5–8 years or so, without decline in productivity in successive rotations.

Whole-tree harvesting is justified by some managers on the grounds of higher efficiency in harvesting costs, and some managers claim higher pulp wood recovery. Total biomass utilisation for bioenergy is a growing business of interest. These practices can cause site deterioration and this should be weighed against short-term benefits. Loss in fertility is not easily compensated for by adding fertilisers. For example, the efficiency of uptake of N by young trees may be 10–20% of the total amount of N added in fertiliser applied at planting and in the following year, and the remainder may be lost or partly immobilised. Replacement of, say, 300–500 kg N ha^{-1} and other nutrients (sequestered in organic matter and typically lost in total biomass harvest or postharvest burn in a eucalypt stand, e.g. Figure 4) would require high amounts of fertiliser applied to compensate for the loss. It is not simply a matter of adding fertiliser containing 300–500 kg N. It is not practical to add such high rates of fertilisers within a short rotation without potential adverse effects on the ecosystem and off-site impacts, nor is it likely to be feasible or economically sensible.

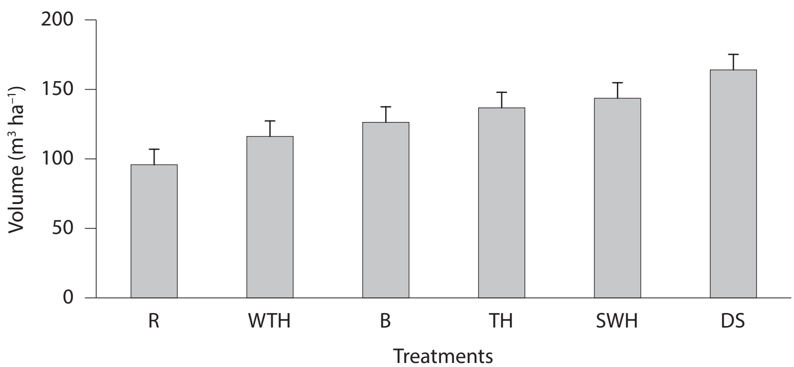

Figure 5. Impacts of sequential removal and changes to above-ground biomass after harvest of the first rotation on the growth of the next stand of eucalypt hybrids at the end of the rotation in Congo. Revised from Laclau et al. (2010) and Paul Laclau pers. comm. 2013. Error bars show standard error of difference of treatment means. R = litter removed, WTH = whole-tree harvest, B = all slash and litter burned, TH = only merchantable wood and bark harvested, SWH = debarked at stump, DS = double slash.

Judicious use of fertilisers has a role in sustainable plantation forestry, but forestry will be better served in the long term by adopting and further developing management that promotes conservation of site resources and minimises the dependency on fertilisers. The benefit of organic matter retention on growth is more than what can be gained by fertiliser application even at sites where soil organic carbon (SOC) concentration levels are relatively modest to high. For example, Hardiyanto and Nambiar (2014) found that at an *A. mangium* site removal of above-ground biomass reduced volume production by 18–20% compared with retention, but application of P, Ca or K gave no significant growth response in the next rotation (Hardiyanto and Wicaksono 2008; Hardiyanto and Nambiar 2014). Similar results have been found with *A. auriculiformis* in southern Vietnam (Huong et al. 2008). This suggests that retaining slash and litter conferred benefits beyond what can be attributed to improved nutrient supply.

Apart from burning and ploughing, we observed that at some sites, after wood harvest, the remaining slash was raked and transported out of sites and stumps were uprooted and transported for bioenergy. Harvesting slash, litter and uprooted stumps for bioenergy from plantations grown for wood production, without detailed understanding of the impacts of such practice on soil and without a practical strategy for restoring soil fertility, is not a route to sustainability and green energy.

Soil organic carbon

The impacts of site management on SOC may differ when comparing afforestation (when plantions are established on previous agricultural land) and replanting or coppicing at a plantation site through successive rotations. Paul et al. (2002) compiled and analysed data from plantation sites that were under afforestation, with a change in land use from pasture or crop to plantation forests, from tropical, subtropical moist, temperate, and continental moist environments, and representing a range of site history, disturbance, species, rotation length, management, and sampling protocols. Although there was much variation within the dataset, the general conclusion was that, on average, SOC decreased by 3.46% per year in the surface 0–10 cm soil and by 0.63% in the upper 0–30 cm of the soil during the first 8–10 years after planting. Changes in total SOC predicted by a process-based model in response to afforestation and reforestation (replanted after one or more harvests) gave an average predicted rate of decrease of 1.7% of the initial amount per year (0.79 t C y^{-1} ha^{-1}) over the first 10 years and recovery with an upward trend in SOC occurring from about age 10–40 years (Paul et al. 2003).

What is the fate of SOC during the inter-rotation phase under various management practices? Smethurst and Nambiar (1995) examined the changes in SOC at a second-rotation *Pinus radiata* site on sandy soil, in a Mediterranean climate with cool, wet winters and warm–hot dry summers, in South Australia. The previous stand was harvested and the residues were windrowed and burned. These operations would have caused substantial loss of surface organic matter, and some surface soil. The soil was then disc ploughed and harrowed. Weeds were controlled by herbicide application in a strip spanning the tree rows or across the whole plot. There was no post-planting soil disturbance and trees grew vigorously. The changes in SOC in the top 15 cm of soil during the next 30 months showed a reduction from 25 g kg^{-1} to 19 g kg^{-1}. The trend between 30–42 months suggested no further changes.

When stands with closed canopies are clear-felled and slash is removed (e.g. windrowed), surface soil temperatures can rise by 10–20% above those under the canopy. Ploughed soil that has been turned over and mixed tends to undergo more frequent wetting and drying cycles and more exposure to the air, hastening organic matter decomposition, N mineralisation and leaching. Litter is a large pool of carbon in plantations at the global scale (Paul et al. 2002), as well as in short-rotation tropical plantations, so conservation of litter and slash at the site is critical for sustaining production (Nambiar and Kallio 2008). (See *Inter-rotation management* in Chapter 3.) Organic matter inputs would be different both in quantity and quality, depending on site history at the start of the rotation.

Figure 6 shows results from an *E. grandis* site in Brazil where logs alone were removed, slash and litter were retained undisturbed, and the site was replanted under minimum tillage. The soil is a Haplic Ferrosol, 77% sand, pH $CaCl_2$ 3.5, and bulk density 1.25 g cm^{-3}. The site management regime applied to the plots is the common operational practice. In both the 0–5 and 5–10 cm soil layers, SOC concentration remained stable from clear-cutting the first rotation to the end of the second rotation with a small increase by the end of the second rotation at age 7 years in the 0–5 cm soil. This result—no reduction in SOC—is consistent with those from a study on *E. globulus* plantation in Western Australia (Mendham et al. 2008) and from a range of sites described and discussed later (Section 3.4, Table 11).

The conclusion from the review and model predictions by Paul et. al (2002, 2003) showing a general decline in SOC from planting to about age 8–10 years before recovery, and results from the second-rotation *Pinus radiata* site described above (Smethurst and Nambiar 1995), are not fully supported by results from any of the sites and species in the network study on second-rotation sites (Nambiar 2008; Table 9). These differences in results may be partly due to the fact that at many sites reviewed by Paul et al. (2002, 2003) and the site studied by Smethurst and Nambiar (1995), there were significant postharvest disturbances including ploughing, compared with the zero-tillage management deployed at the network sites (Table 9). When replantings of second rotations were managed in ways that conserved the site organic matter and imposed little disturbance, the level of SOC in the top soil layer remained stable with small but gradual increase over time (Table 11, Section 3.4).

Conservation of organic matter is critical for eucalypts (which unlike acacia species, do not fix atmospheric N) because SOC is the primary repository of soil N and a large source of most major plant nutrients. Figure 7 shows the relationship between SOC and total soil N in a range of subtropical and tropical second-rotation sites (including site management treatments within some sites. For details see Nambiar 2008). There is a strong linear positive correlation between SOC and N in both acacia and eucalypt plantations, with soil N increasing as SOC increased (Figure 7). Litter and slash are major sources of nutrients other than N in tropical plantations (Nambiar 2008). There are significant positive correlations between surface SOC and N (R^2 0.89), eCEC (R^2 0.97), exchangeable bases K (R^2 0.81), Ca (R^2 0.50) and Mg (R^2 0.91) in second-rotation subtropical pine plantations (Smith et al. 2008). Furthermore, soil organic matter has a strong positive relationship with key biological, chemical and physical properties including soil strength, porosity and soil water-holding capacity.

Soil-available water

In the previous sections the impacts of management on soils were discussed. Most planted species have specific climatic requirements, especially in their physiological ability to cope with stresses such as water deficits. For example, *E. globulus* can grow in soils from siliceous podzolised sand containing less than 5% clay to those with 60% or more clay (such as those mentioned in Table 2). Because of its particular physiological attributes, it is highly sensitive to soil water deficit and prone to drought-induced mortality (White et al. 2009), especially if it has access to good water supply in the early years of the rotation. Even when soils low in chemical fertility can be supplemented to a certain extent with nutrient additions in fertilisers to improve production,

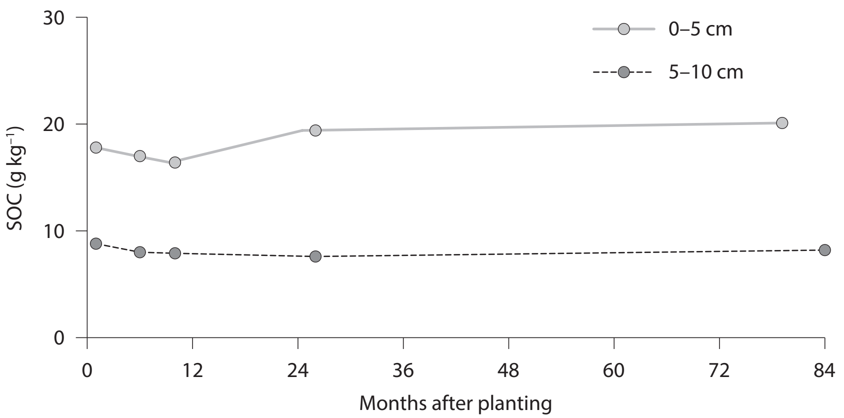

Figure 6. Changes in soil organic carbon (SOC) in the surface soil during a second-rotation plantation of *Eucalyptus grandis* in Brazil (re-drawn from Gonçalves et al. 2008b)

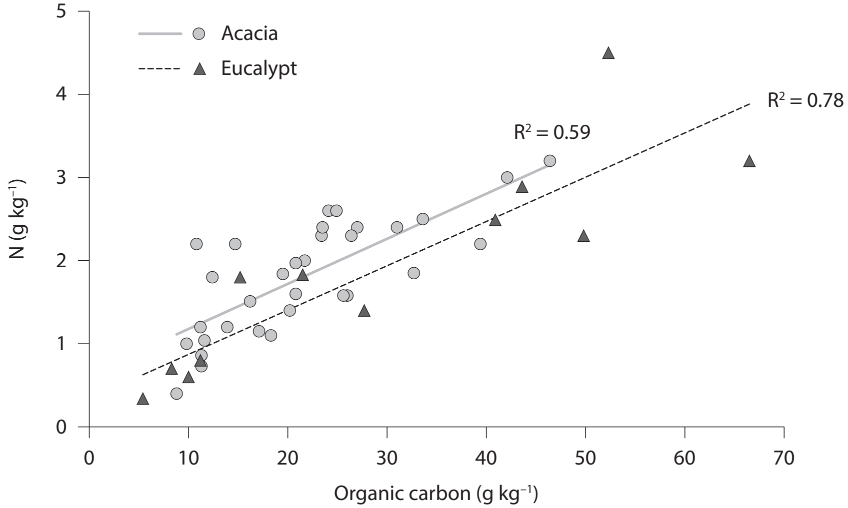

Figure 7. Relationship between soil organic carbon and nitrogen in the surface soils in subtropical and tropical short second-rotation plantation sites. Compiled from various sources including Nambiar (2008); and personal communications.

a growth response can occur only if there is adequate soil-available water and if there are no constraints in soil physical properties, such as high soil penetration resistance due to compaction or eroded soil profiles that impair root growth and proliferation.

Productivity depends on geology, soil type (which can vary within a short distance), landform (terrain and elevation), and climatic factors, including the amount and distribution of rainfall, temperature and events such as frost and drought. Soil-available water is often an overriding factor determining the productivity of plantation forests. In many cases, volume and depth of soil suitable for root development is, arguably, the most critical soil factor determining production. In *E. globulus* plantations in Western Australia nearly all the variation in volume growth rates across sites could be explained by a combination of climate wetness index and soil depth (White et al. 2009). Similarly, two key variables—vapour pressure deficits and soil water availability—accounted for most of the variation in growth across a very large area of eucalypt plantations in eastern Brazil (Almeida et al. 2010). Further work from Brazil showed that soil-available water can be an overriding site variable, determining growth rates in areas with seasonal water deficit (Stape et al. 2010).

Total annual rainfall is not a reliable measure to explain growth rates or to understand the scope for improving production with inputs, because the net water available to the stand throughout the rotation depends on factors including frequency and seasonality of rain, evapotranspiration, soil water-holding capacity, and site and stand management.

Some options for managing available soil water and improving water use efficiency include:

- conserving organic matter, especially on moderate to steep slopes
- managing soil in ways that do not cause erosion (see Photo 29) or degrade soil structure (see Photo 34)
- improving soil water infiltration and rooting by deep ripping.

Controlling competing weeds is an assured way to increase the share of soil water and nutrients available to planted trees, and may also increase access to light, depending on the canopy development of the competing plants.

3.3 Repeated ploughing to control vegetation: effectiveness and impacts on trees and soil

The nature and intensity of harvesting at the end of a rotation and the subsequent site management practices used to re-establish the next crop can have major effects on the plantation ecosystem.

In temperate environments (countries such as Australia, Chile, New Zealand and USA) where plantation forests are a major resource, practices that minimise site disturbances and negative impacts have been substantially adopted. In these cases, major perturbations to the plantation site cease after planting, until clearfelling. Similarly, for eucalypt plantations in Brazil, minimum-impact management is the norm. Our field visits (see Chapter 4) and many discussions with local managers identified an important, wider issue: the potential impacts of the intensity of site cultivation throughout the rotation as practised in parts of SE Asia. This section is devoted to that analysis.

Ploughing is no longer practised in Indonesia by companies that have adopted minimum-tillage practices. Burning slash is not permitted by law in Indonesia; despite this, fire outbreaks do occur in forest-farm landscapes. Elsewhere, as reported in Chapter 4, even when harvesting itself is largely manual, inter-rotation management practices often start with major site disturbances including bulldozing (Figures 18 and 19), removal of biomass (including stumps), and burning slash (Figure 29). These disturbances may be followed by deep ripping and ploughing along the slopes. In addition, managers resort to repeated ploughing to control weeds to avoid competition with trees and to reduce the fuel load for fire control. Some managers we spoke to also assumed that repeated ploughing was 'better for the soil' and may eradicate soil-borne diseases.

Repeated ploughing is a near-universal practice in block plantations in Thailand. It is common in parts of China and Vietnam in locations where the terrain is not too steep. In Laos, which currently has only a small area of plantations, establishment of new eucalypt plantations involves bulldozing and then burning the biomass in degraded forests. Burning to clear the vegetation is necessary to spot and destroy unexploded ordnance in Laos. But this is followed by repeated ploughing for intercropping with rice or cassava or for weed control in eucalypts planted in wide rows.

Herbicide technology has not been adopted by many growers in Thailand. It has been tried in experiments and at small scales by some companies in Vietnam and is used by some but not all major growers in China. In Sabah, reliance on manual labour for weeding has resulted in overgrown weeds and poorly growing trees. Reliance on immigrant labour creates social problems and is unlikely to succeed in the long term. This realisation is stimulating adoption of herbicide technology in Sabah. In Laos, the idea of using herbicides in forestry invokes fear in the communities of food and water contamination.

An understanding of the nature and intensity of impacts is necessary to aid this discussion. At the current frequency of ploughing that we have observed (e.g. in Thailand), by the end of the first planted rotation and a coppice rotation together spanning 8–10 years, many sites had inter-rows ploughed up to 25–30 times. Repeated ploughing is also common in parts of China and Vietnam (see Photos 20–21, 31). At some sites, soil was ploughed when wet, leading to slicing and turning of the clayey soil. These slices turned into hard clods with smooth glazed surfaces when they were exposed and dried. Displaced soils were turned over, creating mounds along the tree rows and 1.0–1.2 m wide depressions between the rows (Photo 20). These were prone to waterlogging, in some instances because of the formation of a dark and dense layer below the common plough depth (which may impair infiltration), or they became pathways for surface water flow and soil erosion, depending on topography and soil type.

Is ploughing effective as a weed-control practice to improve tree growth and for fuel reduction?

Ploughing operations, regardless of frequency, reduce weed growth only between tree rows, about 50% of the total land area, as they cannot reach close to the trees (if they did, the damage to branches and roots would be severe). The 1.0–1.5 m wide strips centred on the tree rows often had a dense cover of weeds competing with the trees (see Photos 23–24). They spread and seed onto the tilled soil surface and subsequent weed growth justifies the next ploughing. For effective weed control, regardless of the means, the spatial location of the weedy and weed-free areas should be the opposite of what is achieved by ploughing. What is required is an appropriately wide weed-free strip centred along the tree rows, and some vegetation remaining in the inter-rows.

Ploughing may reduce plant fuel and thus the spread of fire, but substantial amounts of weeds remaining along the tree rows can still damage trees in the event of a fire. According to managers, common sources of ignition include smoking by labourers or sparks from exhausts of motorcycles and other vehicles. We were also told that fires are sometimes lit deliberately by the local people in response to conflicts or to create jobs (allegedly forcing the companies to replant). In the absence of any objective appraisal of the biophysical and social aspects of fire risks, repeated ploughing of the entire area continues as the only fire-reduction strategy. In some plantations in southern Vietnam, apart from ploughing, seasonal litter falls are swept or raked, heaped and burned. Apparently this is to reduce fuel load (although the amount of litter fall in a season under slow-growing stands would be small, and acacia litter decomposes rapidly), leading to visible adverse effects on stand growth. Ploughing at the frequency practised imposes a significant cost on production when combined with the low to medium growth rates achieved on these sites (Figure 20, Table 18). Thus, based on our observations, the current practice seems neither effective nor efficient as a weed-control and fuel-reduction strategy.

Commercial plantation forestry has not been possible, anywhere, without proper methods for managing ground vegetation, and there are better options than repeated ploughing. Contemporary research-based approaches (Gonçalves et al. 2008a) do not aim for zero tolerance of all vegetation other than the commercial trees. Rather, they aim to optimise the balance between production goals and acceptable limits to vegetation. Under such management, some weeds can be considered as a source of organic matter and the impact of their management on SOC and nutrient cycling also warrants attention. However, in several large regions of SE Asia, repeated ploughing has become entrenched as the only way to reduce weeds. We found no systematic analysis of the causes of fire or reliable records of the degree or frequency of fire in each of the environments, nor attempts to try other fire-management approaches including creating firebreaks along the roads, educating workers and establishing participatory programs with the local communities.

In the following sections we briefly review the potential impacts of repeated ploughing on fine root dynamics and SOC.

Impacts of repeated cultivation on root systems

After transplanting from the nursery to the forest site, planting stock invariably undergo transplanting stress, commonly water deficit, partly because roots are clustered and confined to the planting hole and there is limited contact between roots and soil. A proportion of the transplanted roots will die. Recovery from stress depends strongly on root regeneration (initiation and survival of new root apices and their growth rates). New roots may be initiated directly from the taproot or from a set of healthy transplanted roots, especially first-order lateral roots (those originating from the tap root). These new members grow and branch radially in the top soil layers and vertically through the soil profile. If conditions are congenial for growth, especially if root growth is not restricted by soil penetration strength, root systems will expand to occupy the area between and within tree rows within about 1 year of planting.

A typical distribution of fine roots in soil profiles under *E. grandis* plantations in Sao Paulo state, Brazil, is shown in Figure 8. This study included 16 sites where Site Index (SI), expressed as mean dominant height at age 6 years, ranged from 22–32 m. The three lines in Figure 8 represent the root distribution as means of all 16 sites, three with the highest SI, and three with the lowest SI. Root concentrations in the soil both in the surface layer and at depth increased as the SI decreased; that is, the lower the productivity of the stand, the higher the amounts of fine roots produced. In all cases, amounts of fine roots were highest in the top soil layers and decreased exponentially with depth (Figure 8). Despite the two-fold difference in the amounts of roots between sites at 0–10 cm soil, all values decreased substantially below 30 cm depth. This pattern of fine root distribution characterised by the highest fine root density in the top 10–20 cm of soil and a sharp, near exponential decrease from 25–30 cm and below has also been found in plantations of *Pinus radiata* (Nambiar 1990) and a range of eucalypt species grown in a wide variety of soils and environments (Bouillet et al. 2002; Falkiner et al. 2006; Grant et al. 2012).

As noted earlier (Chapter 4), at some sites examined during our field visits, repeated ploughing appears to have induced the formation of a dense, indurated soil layer about 25 cm below the soil surface and this may impede root growth. Subsoil compaction can affect stand growth, especially through the reduction in root extension to deeper levels, where young plantations take up water during dry months, as shown for *P. radiata* plantations in Australia (Nambiar and Sands 1992). Laclau et al. (2001) described a relationship between fine root density and soil strength in eucalypt hybrid plantations in Congo and noted that soil strength increased during the dry season.

Most eucalypt plantations in SE Asia are coppiced at least once following the first planted rotation.

Coppicing brings about a number of eco-physiological changes in trees. The prevailing view is that the taproot and secondary thickened coarse roots (sometimes categorised as those more than 3 mm in diameter) ramify through the profile and form a ready-made support structure for the uptake of water and nutrients to support the growth of new shoots from cut stumps. However, few, if any, experimental studies have examined this aspect critically. Fine roots, unlike coarse roots, have a relatively short lifespan and decompose readily. So the amount of roots measured at any one time is not a true measure of their production. Given this limitation, Teixeira et al. (2002) reported an increase in the net amount of fine roots (≤1 mm) in a *E. urophylla* plantation in Brazil, from 702 kg ha^{-1} before stand harvest to 1,349 kg ha^{-1} 60 days later with a small steady increase in mass to 330 days after harvest. In contrast, another study found that 60 days after harvesting a 9-year-old *E. grandis* stand the net root density was only 50% of the preharvest values (Mello et al. 2007). There appears to be no information on root dynamics, including the effects of coppicing, in plantation systems in SE Asia.

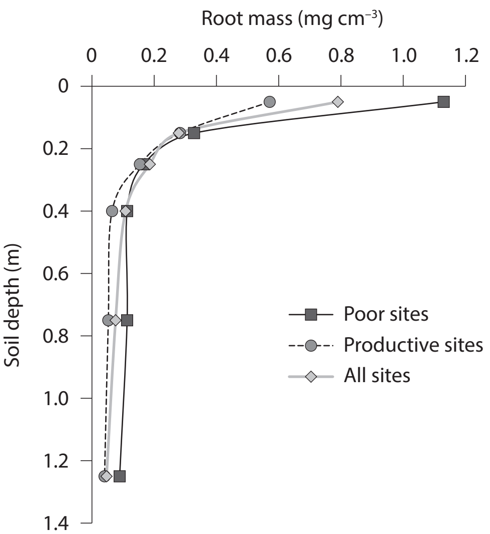

Figure 8. Distribution of fine roots in *E. grandis* plantations at age 6 years in Brazil (from Gonçalves and de Miranda Mello 2000)

Because the fine roots are predominantly in the top 10–20 cm of soil regardless of soil types and age of the stands, repeated ploughings will continually mutilate and cut back about 90% of the fine root network in some 50–60% of the plantation area in the inter-rows. The effects of this disturbance to the root network on tree growth may be severe during dry months, following ploughing at the end of the rainy season, when fine root growth is likely to be substantially less than in wetter months, even without any site disturbance (Mello et al. 2007; Nambiar unpublished data). Coppicing and subsequent repeated ploughing would have major effects on fine root growth and their survival. We are not aware of any study on root dynamics in acacia plantations but it is reasonable to assume that the patterns described above would apply to acacia plantations.

The main points to be recognised include:

- Fine roots are concentrated strongly in the surface soil and they will be repeatedly cut back and damaged by repeated ploughing and discing.
- Rooting density (root length/soil volume) in eucalypts is low, 2–4 cm cm^{-3}, compared with 32–44 cm cm^{-3} in common weeds, 60–100 cm cm^{-3} in pastures and about 20 cm cm^{-3} in cereals).
- The opportunity for fine root turnover to contribute to soil organic matter gain and nutrient cycling is likely to be much reduced if ploughing repeatedly curtails fine root growth and their natural cycle of growth and senescence.
- The formation of hard pans and potential waterlogging resulting from repeated ploughing may lead to high-strength soil horizons, which may restrict root penetration and growth to deeper profiles.
- Each time roots are cut, trees will have to invest more assimilates in root regeneration. If repeated soil disturbance is avoided, a proportion of the fine roots would become thicker (by secondary thickening and suberisation) and join the network of coarse root architecture as trees grow taller. This root development is an important process to support tree stability, especially in sites prone to high wind.
- Furthermore, at all ploughed sites we visited, repeated ploughing prevented the development of the litter layer, which is important for a number of ecosystem processes. Fine roots at the litter–soil boundary and in the top soil horizon are the most functionally crucial part of root geometry for uptake of nutrients, which are mostly concentrated

in the surface soil horizon and litter. These fine roots also contribute to water uptake, although deeper roots play the key role in water uptake.

What are the likely effects of repeated ploughing on soil organic carbon?

There is no experimental work that we are aware of that has examined the potential impacts of repeated ploughing on soil properties and or tree growth in SE Asia. Neither is there any directly relevant information from tropical plantations elsewhere in countries such as Brazil because intensive soil cultivation has been replaced with zero-tillage practices there for over a decade. However, there is significant information about the impacts of intensive cultivation in agriculture in recent decades on soil carbon and other soil properties. The frequency of ploughing in plantation forestry observed in some local regions of several countries covered in this report (China, Thailand and Vietnam) is more akin to practices in agriculture than to forestry. Even for annual agricultural crops, it is rare to see three ploughings per year, as we observed in some plantations (Chapter 4).

What can we learn from crop agronomy? When forests are cleared for agriculture, large amounts of SOC are decomposed and released as carbon dioxide. When a forest in Sao Paulo, Brazil, was cleared, converted to sugarcane and cultivated regularly, the SOC decreased from 43.4 g kg^{-1} to 13.2 g kg^{-1} in 22 years and 16.1 g kg^{-1} by 60 years, with corresponding declines in labile carbon (Lefroy et al. 1995). Reductions in soil carbon pools were 63% of their base levels. Some estimates suggest that many soils in the USA may have lost 30–50% of the SOC they held before they were cultivated (Kucharik et al. 2001). A comprehensive review of soil carbon sequestration potential in Australian agriculture concluded that conversion of native land to agriculture involving cultivation and repeated cropping has resulted in decreases in SOC stocks in the order of 40–60% from pre-clearing levels (Sanderman et al. 2010).

Among the extensive reviews of many studies included in the Sanderman et al. (2010) review, two examples are relevant to this discussion: (i) a chronosequence study which showed that when land was continually cultivated, SOC dropped from a base level of 22 g kg^{-1} to 15 g kg^{-1} in 10 years and to 6 g kg^{-1} by 45 years, a 73% reduction and (ii) applying a single tillage to a plot that was not tilled (NT) for the previous 14 years resulted in large losses of SOC from the soil, but applying NT to a previously tilled plot resulted in no significant gain in SOC. Soil cultivation (tillage) disrupts soil aggregate structure, which would increase decomposition rates of carbon pools, but the re-formation of stable aggregates that protects carbon pools is a much slower process, even after tillage has stopped (Balesdent et al. 2000). Our field observations at sites that were repeatedly ploughed (Sections 4.3 and 4.5) confirmed that at some sites soils have lost all structural elements including aggregates to a depth of 25 cm. A number of studies in agricultural systems show that the rates of loss in SOC in response to soil management are faster than rates of recovery (Sanderman et al. 2010). Based on modelling studies on *Pinus radiata* and *E. globulus* plantations grown in Australia, the predicted general rate of decrease in SOC during the first 10 years after planting was 0.79 t C ha^{-1} y^{-1} (1.7% per year) and the predicted rate of increase from age 10–40 years was 0.46 t C ha^{-1} y^{-1} (0.82% per year), much slower than the rate of decrease (Paul et al. 2003).

The discussion above shows that it is likely that repeated ploughing in short (5–8 year) rotations may lead to declining SOC levels in the soil, which would likely have a negative effect on productivity. We know that if above-ground biomass (minus wood) is retained at sites and no tillage is applied for replanting, SOC levels can be maintained or improved in short-rotation forestry (Figure 6, Table 9).

We conclude that there is a serious need to critically examine the impacts of intensive tillage on soil organic matter, nutrient pools and soil physical properties in plantations in some parts of SE Asia. Removal of above-ground biomass after each harvesting cycle will remove a large potential input of organic matter to the soil. Furthermore, because it is not feasible to plough a clearfelled site if slash is retained, removal of above-ground biomass becomes a prerequisite or justification for ploughing.

The effects of repeated ploughing on soil, weed control and plantation growth have seldom been studied because this is not a common practice in major plantation-growing areas where much of the plantation forestry research originates. There are no site-specific experimental data applicable to plantations in SE Asia. It is likely that repeated ploughing poses risks to sustainability and may well be an underlying reason for the relatively low and variable productivity obtained in operational plantations in some regions (see Table 18 in Chapter 5). Clearly, this is a priority area for future research.

3.4 Can productivity and soil properties be maintained over successive short rotations?

In the previous section we discussed the principles underpinning the interrelationships between management and sustainable production. Some have argued that there may be intrinsic site- and soil-based constraints on managing production in successive rotations of exotic monoculture in short-rotation forestry. A well-known report, 'Fast-wood forestry' (Cossalter and Pye-Smith 2003), examined the myths and realities of some of these and other arguments.

In a long-term study, Evans (2005) followed the height growth of four successive rotations (15–17 years each) of *Pinus patula* experimental stands in Usut Forests in Swaziland and concluded that, under normal management treatments, at age 5–6 years trees in the fourth rotation were 6–10% taller than those in all preceding rotations. Evans argued that in this case sustainable production can be maintained. However, little explanation was possible, because only heights were measured throughout. Short-rotation forestry in SE Asia is managed under very different environments and expectations.

The biophysical processes governing plantation productivity were discussed in a multidisciplinary book (Nambiar and Brown 1997). The ideas that emerged from the book and the rate of expansion of short-rotation forestry prompted the development of a coordinated international network study by the Center for International Forestry Research (CIFOR) during 1998–2008, with the aim of examining questions about the productivity of successive rotations. A unique feature of the study was that a set of core treatments was implemented uniformly across all sites with additional optional treatments appropriate for the local situations. All harvests were manual and site disturbance was kept to the minimum in core treatments. Results from this network of trials have been cited in various contexts earlier. Although the role of CIFOR in the project was completed in 2008 and the results up to that time were published (Nambiar 2008), work has continued at several sites. Among these, experiments at two *A. mangium* sites in Sumatra and one *A. auriculiformis* site in Vietnam have progressed to the third rotation, results from which are presented in the country reports from Indonesia and Vietnam (Chapter 4). Using more recent and updated results beyond those provided in Nambiar (2008), we can try to answer, to some extent, three pertinent questions that are still being asked:

- Can productivity of tropical plantations be maintained at sites for more than one rotation?
- What is the scope for increasing production with management and across key species?
- What types of changes might there be in soil properties?

Can productivity be maintained?

Questions about productivity across multiple rotations cannot be answered with certainty, because as noted earlier, the history of tropical plantations is recent and relevant data are not easy to find (see Chapter 5). Literature reporting such comparisons is scant, even for temperate plantation forestry, despite its long history. The CIFOR network program included 14 sites in the subtropics and tropics and two in Mediterranean environments (see Nambiar 2008 for details). It examined the productivity of first-rotation (1R) and second-rotation (2R) stands in commercial management units across 10 eucalypt, four acacia, one hybrid pine and one Chinese fir site. Earlier results (Nambiar and Kallio 2008) showed that trees at 11 of 16 sites grew at faster rates than in the corresponding previous crop, some substantially so. Trees at the other five sites grew at the same rate in both rotations. The regression between MAIs of 1R and 2R showed that all sites were consistent with a simple relationship confirming the influence of site factors on production, and a general increase in production in 2R across a wide range of growth rates. At the time those earlier results were provided (Nambiar and Kallio 2008), none of the four acacia sites were at the end of the second rotation, so their MAIs were indicative. Full rotation results for 1R and 2R for all eucalypts and acacia sites are now available, and are presented in Figure 9. The MAIs for 2R are the mean values of a range of management practices, so they are representative of 2R growth rates at these sites. The dotted line in Figure 9 shows the 1:1 parity. Results show simple relationships between 1R and 2R MAIs across all sites and species. Second-rotation yields for the majority of sites were higher (in some cases nearly three times higher) than the first, and others were close to the 1:1 line with no case in which there was a clear decline in production.

The limitations in interpreting the differences in growth rates between rotations are known (O'Hehir and Nambiar 2010). For example, growth rates are influenced by factors including the planting of different genetic material, climate, stocking and management. For the 2R, planting stock was genetically improved and all trials were maintained under adequate weed control. However, the net benefit of improved management on production is clear.

What are the prospects for increasing production at these sites?

Table 10 summarises the changes in wood production in response to management inputs at 10 eucalypt and three acacia sites at the end of the second rotation across a range of environments and growth rates. The lowest and the highest volumes were obtained from the range of treatments (planting stock remained the same within each site and weeds were controlled at all sites); the lowest was usually associated with depletion of organic matter and the highest with the retention of organic matter and supply of additional nutrients in some cases. The main points are that the prospects of increasing production with better site management vary but are often good, and that opportunity for increasing production applies to both low- and high-quality sites and across a range of species and growing environments. Scope for increasing growth rates is very high at some eucalypt sites and in acacia in southern Vietnam; the high responses were obtained through the cumulative benefits of slash and litter conservation, weed control and N and P supplementation.

What are the trends in changes in soil properties?

A common concern about short-rotation forestry in the tropics has been the consequences for the soil of the removal of biomass and nutrients by harvests at short intervals of 5–10 years. Several reviews have summarised the potential depletion of nutrients, especially base cations (K, Mg and Ca), and raised the prospect of increasing soil acidity (Folster and Khanna 1997; Nykvist 2000; Mackensen et al. 2003). Information showing very high net loss of carbon and nutrients in biomass removal, volatilisation and particulate losses during burns, and subsequent leaching losses, when a wet tropical forest in Amazonia was clear-cut and the debris was burned for conversion to other land uses (Mackensen et al. 1996), reinforces the potential risks induced by management.

From the network project, we now have relevant results from the end of the first to the end of the second rotation, enabling an examination of the direction of changes in soil properties over a full rotation period of 6–10 years. Based on earlier results, Tiarks and Ranger (2008) concluded that, across all 16 sites,

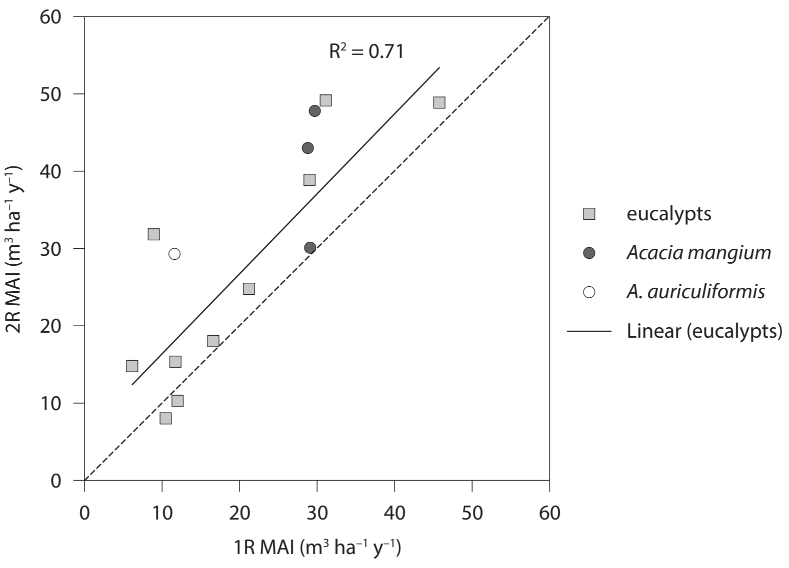

Figure 9. Relationships between growth rates of first (1R) and second (2R) rotation plantations in experiments of the subtropical and tropical network project. Note: For details see Nambiar (2008) and Nambiar and Kallio (2008).

changes over the rotations in SOC, N, pH and exchangeable cations were small and transient and there was no indication of a decline in surface soil properties, unless extreme treatments were applied such as total removal of above-ground biomass. Trends in the direction of the changes (across core treatments) with updated results for six eucalypt and three acacia sites are summarised in Table 11.

In general, changes in soil properties were small and no changes in properties were consistent across sites. Soil pH remained stable, while there were indications of reduction in exchangeable K in four out

Table 10. The lowest and highest amounts of wood produced in response to inter-rotation management treatments at a range of second-rotation sites

Site	Species	Stand age (y)	Lowest volume (m^3 ha^{-1})	Highest volume (m^3 ha^{-1})	Gain (%)
Congo: Pointe-Noire	*Eucalyptus* hybrid	7.0	84.1	160.9	91
India: Kerala					
Punalla	*E. tereticornis*	6.5	78.2	278.0	256
Surianelli	*E. grandis*	6.5	166.7	269.5	62
Vattavada	*E. grandis*	6.5	328.4	350.0	7
Kayampoovam	*E. tereticornis*	6.5	87.4	140.0	60
China: Guangdong	*E. urophylla*	7.5	38.9	52.5	35
Brazil: Itatinga	*E. grandis*	8.7	176.2	276.7	57
South Africa: KZ-Natal	*E. grandis*	5.5	123.0	146.0	19
Australia					
Busselton (WA)	*E. globulus*	10.0	74.0	122.0	65
Manjimup (WA)	*E. globulus*	10.0	434.0	487.0	12
Indonesia: Sumatra					
Riau	*Acacia mangium*	8.0	247.0	297.6	20
Sodong	*A. mangium*	7.0	314.0	366.0	18
Vietnam: Binh Duong	*A. auriculiformis*	6.0	165.2	197.7	20

Source: Revised and updated from Nambiar and Kallio (2008)

Table 11. Change in soil properties in the surface 10 cm from the end of the first rotation to the harvest of the second rotation.

Site	Species	Stand age	SOC	Total N	Extr. P	pH	K	Ca	Mg
		(y)	(g kg^{-1})	(g kg^{-1})	(mg kg^{-1})	(c mol_c kg^{-1})			
Congo: Pointe-Noire	*Eucalyptus* hybrid	7.0	↔	↔	NR	NR	↔	↓	↔
China: Guangdong	*E. urophylla*	7.5	↑	↓	↔	↔	↑	↑	↔
Brazil: Itatinga	*E. grandis*	8.7	↔	↔	↓	↔	↑	↔	↑
South Africa: KZ-Natal	*E. grandis*	5.5	⇈	↑	↔	↔	↔	↔	↔
Australia									
Busselton (WA)	*E. globulus*	10.0	↔	↔	↔	↔	↓	↔	↔
Manjimup (WA)	*E. globulus*	10.0	↔	↔	↔	↔	↓	↔	↔
Indonesia: Sumatra									
Riau	*Acacia mangium*	8.0	↑	↔	↔	↔	↓	↓	↓
Sodong	*A. mangium*	7.0	↔	↔	↓	↔	↔	↔	↔
Vietnam: Binh Duong	*A. auriculiformis*	6.0	⇈	⇈	↓	↔	↓	↔	↓

↔ no change ↑ increased ↓ decreased ⇈ statistically significant increase NR not reported
Increases and decreases are only trends and not statistically significant unless specified.
Source: Revised from Tiarks and Ranger (2008) and updated from personal communications from network partners. See Nambiar (2008) for experimental details.

of nine sites. There was an indication of a decline in extractable P for the acacia sites. Soil organic carbon levels remained stable or increased at four sites. A more detailed illustration from the eucalypt site in Brazil where SOC was followed annually at 0–5 cm and 5–10 cm depths confirms this trend (Figure 6), paralleling the conclusion drawn from the *E. globulus* sites in Western Australia (Mendham et al. 2008).

Concerns about soil acidification (declining pH) in tropical acacia plantations have been expressed (although seldom substantiated by data), because these species can grow rapidly, enabling large amounts of biomass and mineral nutrients to be removed at harvest, and they can fix atmospheric N, which in turn may increase N leaching and carry bases in the leachate. Because this is a recurring concern, a discussion is warranted. Yamashita et al. (2008) compared pH in soils under stands of first-rotation *A. mangium* with soils from secondary forests and *Imperata* grasslands in South Sumatra. They found no significant difference in soil pH_{H2O} up to 30 cm depth, between secondary forests and *A. mangium* plantations. In fact, pH_{H2O} in *A. mangium* was slightly higher than in secondary forests, and pH_{KCl} under *A. mangium* was generally higher than in both secondary forests and *Imperata* grasslands. They also found soils under *Imperata* grassland had pH_{H20} that was about 1 unit higher than that under other land uses. Although the authors did not mention this, the slightly higher pH_{H2O} in grassland may have been due to the repeated fires that tend to occur in these grasslands (partly from cultivation by local communities), which could have produced the ash effect and the 1 unit pH rise. Values of pH_{KCI} below 10 cm soil depth were lower in grasslands than in other land. Delta pH results mirrored those for $pH_{H2O.}$ Thus the difference in pH between grassland and acacia may be due to a pH rise under grass (possibly a burning effect) and not necessarily a decline under acacia, where pH was, as noted earlier, slightly higher than under secondary native forests. Distribution of exchangeable bases in the profile showed similar patterns to those of pH. It is particularly relevant to note that in both their patterns and concentrations, bases in soils under native forest and acacia were identical. In our view these results do not support the conclusion that at the sites studied by Yamashita et al. (2008), acacia plantations per se reduced soil pH in one rotation as concluded by the authors.

We know of no other studies that have measured changes in soil with time in designed experiments with successive plantation rotations, as was done in the network study. Tiarks and Ranger (2008) summarised results across 16 sites and concluded that neither slash and litter removal nor the stand growth from first to second rotation influenced soil pH in a significant way through the rotation. The pH results measured annually during the full second-rotation period for three acacia plantations at two sites in Sumatra (Site 1 is a red yellow podzol and Site 2 is Ferric Acrisol) and one site in southern Vietnam (Chromic Acrisol) are presented in Figure 10. Data are from plots where only wood was harvested, and slash and litter were retained, as is now the common practice in Indonesia. The first data point (year 0 in each time series) is the preharvest level measured at the end of the first rotation. Soil pH values fluctuated through the years, in some sites more than in others, but there was no indication of pH changing with stand age. At the southern Vietnam site, pH_{H2O} and pH_{KCl} were measured and both measures remained unchanged across the rotation. When some decline in pH occurred during the early phase of plantation, the values returned to pre-planting levels (Figure 10) under contrasting site management treatments, soils and growing conditions (Hardiyanto and Wicaksono, 2008; Huong et al. 2008; Siregar et al. 2008). Similar results were found at two *E. globulus* sites in contrasting soils in Western Australia measured over 10 years from the end of first rotation (Mendham et al. 2008).

Studies using chronosequences and paired land use approaches that conclude that acacia plantations acidify soil often overlook the confounding effect of differences between contrasting land types. For example, Dong et al. (2012, 2014) compared fallow shrublands in central Vietnam, unavailable for forestry since 1995 following construction of overhead powerlines, with a chronosequence of adjacent acacia hybrid plantations from age 0.5 years to 5 years. Their results clearly show that the fallow land had several soil properties very different from the land under the acacia age series, which themselves seem to have had a varied history (some plots probably being under their second plantation rotation subsequent to 1995). For example, total SOC in the uppermost 20 cm of soil in the fallow land averaged 12.99 ± 1.75 (SE) mg ha^{-1} and that in the plots of 6-month-old acacia was 21.76 ± 0.72 (SE) mg ha^{-1}, some 40% higher. This large difference in SOC is clearly not attributable to 0.5 years of growth of a single acacia crop.

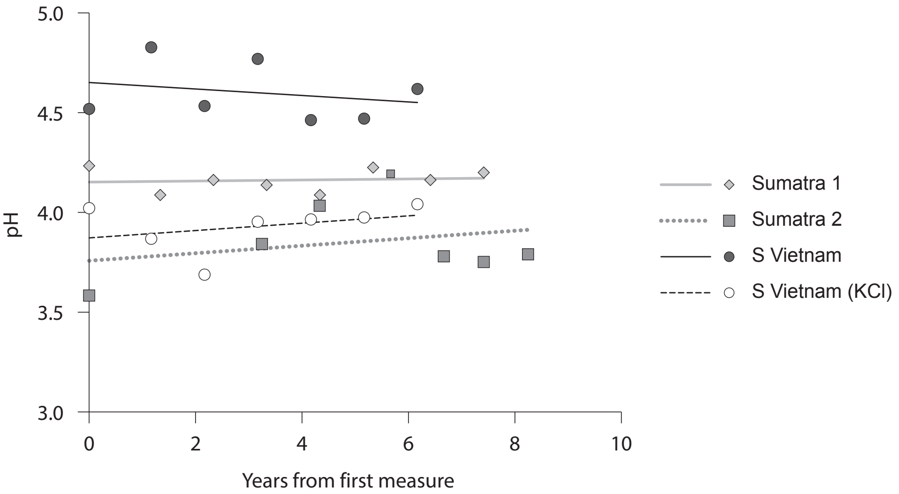

Figure 10. Changes in the pH of the surface 0–10 cm of soil over a full second rotation of *Acacia mangium* at two sites in Sumatra, and *A. auriculiformis* in southern Vietnam. Linear regressions shown by the lines were not significantly different from zero. Source: Hardiyanto et al. (2008); Siregar et al. (2008); Huong et al. (2008) and updated data in pers.comm. to Siregar.

Similar large and unexplained differences in a range of other soil properties (e.g. exchangeable Ca and Na) between fallow land and young acacia stands, not attributable to the growth of the young trees, were reported. Despite such critical confounding problems, and based on a very small difference of 0.1–0.2 units of pH, Dong et al. *(*2012) concluded that soil acidity increased under acacia plantations.

In another matched-plot study involving several sites from contrasting soils and locations in Vietnam, Sang et al. (2013) found that the pH_{H2O} averaged across sites was: plantations 4.38, secondary forests 4.48 and pastures 4.90. The difference between plantations and secondary forests was not statistically different, but that between plantations and pastures was. This relatively small difference in pH, with pastures higher by 0.60 pH units, could have been due to local practices common in Vietnamese farms and is not a reliable measure of decline in pH under plantations or native forests. The cation exchange capacities (CEC, cmol kg^{1}) for plantations, second-ary forests and pastures were 1.08, 0.73 and 1.85 respectively and did not differ significantly. Yet, it was concluded in the abstract that ‘all plantations, but not secondary forests, caused soil acidity’. Soil pH is a fluctuating property and much caution is needed in drawing conclusions based on measurements at one time.

The idea that acacia plantations acidify soils appears to be widespread. Results from designed experiments (Figure 10, Table 11) do not support such a conclusion.

Overall results presented here, and the review of published information, do not show that short-rotation plantation forestry has adverse effects on soil properties if proper management practices are followed. That will not be the case where high-impact operations continue to be practised, such as removing all above-ground biomass from the site, bulldozing to prepare sites for the next rotation or repeated ploughing to control weeds. It is important to build a long-term database from well-designed experiments to monitor and understand the impacts of manage-ment on soils over several rotations, and to use such information to improve management and to address questions from local communities.

Forestry is a long-term business, and can be viable and successful only if the fundamentals of sustainable production over the long term, and multiple rotations, are understood and managed wisely. If productivity fails, the objective of forestry will be lost with it. In the context of plantation forestry, sustainable production does not mean that it has to be achieved with any single species and management regime in perpetuity, any more than it has be achieved by plant-ing particular provenances or clones. In short-rotation forestry, changing from one species to another or planting several species in one estate in response to biological threats or commercial opportunities are logical decisions. Such options can be brought into action, promptly and successfully, only if the productive capacity of the soil and values of the landscape have been maintained or enhanced along the way with science-based and holistic management. Success of any forestry business rests on sustained wood production achieved with environmental care. Simply maintaining production at low or mediocre levels in estates in which production potential could be high is a lost opportunity in land use and value to society (Nambiar and Sands 2013). Cost of production and the value of products are also important considerations.

3.5 Impact of diseases and pests

In this section, the impacts of diseases and insect pests on wood production in acacia and eucalypt plantations are discussed, and we review management options in the context of SE Asia. Acacias and eucalypts are exotic to the region. Some of their diseases and pests have co-evolved with them and some are encountered for the first time in the new environment.

As the area of plantations expanded, the potential spread and impacts of diseases and pests were recognised and manuals of damage symptoms caused by them have been published (Old et al. 2000, 2003; Thu et al. 2010).

Reviews (Garnas et al. 2012; Dell et al. 2008; Wingfield et al. 2008, 2011) suggest that pests and diseases pose severe, and increasing, threats to plantation forests globally. There are several lines of evidence to support this view:

- Increasing global trade and travel lead to the spread of pests and diseases despite quarantine regulations. This is further accelerated by the expanding area of plantations based on few species.
- Plantations in the tropics and subtropics are based on a relatively narrow genetic base, and clonal forestry is becoming a norm. The same genetic material may be planted in adjacent countries. For example, some eucalypt clones are currently planted in two or more of China, Laos, Thailand and Vietnam. This provides relatively uniform host plants for the evolution, multiplication and spread of pests and diseases.
- When exotic species are planted to a new environment they are exposed to new pests and diseases. For example, guava rust, also known as eucalypt rust (*Puccinia psidii*), is a disease native to Latin America that has severely affected eucalypt plantations in Brazil and neighbouring countries (Alfenas et al. 2004). Despite Australian quarantine, this disease has recently appeared in Australia, on *Eucalyptus* and other species of the family Myrtaceae (Kriticos et al. 2013). Similarly, stem wilt/canker disease, caused by the fungi *Ceratocystis acaciivora*, which appears to be native to tropical SE Asia, has spread and is becoming a serious threat to acacia plantations in Sumatra (Wingfield et al. 2011) and Sabah, and has now been found in Vietnam (Dr Pham Quang Thu pers. comm. 2013).

We comment below on the major diseases and insect pests in SE Asia. Diseases and pests are considered separately because their mode of action on plants and their pathways for spreading are different: most insect pests typically consume part of the tree, especially the foliage, whereas a disease affects the physiological functioning of the tree and may kill it. Of course, the two do interact; for example, insect pests may carry disease spores from one tree to another, spreading the disease (Ploetz et al. 2013). Currently, the impact of diseases on productivity of acacia plantations in SE Asia is far greater than the impact of insect pests.

Diseases

The major losses in productivity of acacia plantations are caused by fungal root rots (*Ganoderma* species being the most important agent; Eyles et al. 2008) and *Ceratocystis* stem wilt/canker (Tarigan et al. 2011a). Because of the high levels of mortality they have caused in second and third rotations, growers in Sumatra are replacing acacias with eucalypts. A similar shift has commenced in Sabah, Malaysia. This is likely to have an impact on wood production in the near future because the current growth rates of eucalypts, in general, are lower than those of acacias in these environments (Section 5.2). Better management and ongoing breeding may improve future productivity of eucalypt plantations.

Root rot disease caused by fungal pathogens (primarily *Ganoderma*) and *Ceratocystis* stem wilt/canker reduced tree survival, sometimes drastically. There is a strong relationship between stocking at preharvest inventory and wood volume: the lower the stocking, the lower the yield (Figure 18). Mortality due to root rot tends to increase in successive rotations. Surveys in second-rotation *A. mangium* plantations in Sumatra found that from 3–29% of trees showed symptoms of root rot (Irianto et al. 2006). In subsequent surveys of 109 compartments of *A. mangium* in different regions in Indonesia, the percentage of trees with root rot symptoms increased from 5% in the first rotation to 15% and 35% in the second and third rotation respectively (Mohammed et al. 2012). These data were collected in young stands and, since mortality increases with stand age, losses would be higher by the end of the rotation.

Heart rot diseases are a threat to acacia sawlog production (Potter et al. 2006), as the recovery and quality of sawn boards is reduced if the log is decayed. The percentage of logs with heart rot at harvest ranged from 7–47% in five regions of Indonesia (Barry et al. 2004). However, the impact on pulpwood production would be small, because most of the affected trees had only discolouration or incipient decay; less than 10% of the trees surveyed in any of the regions had hollows or advanced decay.

In Vietnam, pink disease caused by the fungus *Corticium salmonicolor* occasionally infests stands of *A. mangium* and acacia hybrid, killing up to 70% of trees in stands. Infected stands are salvage-logged and the site is replanted to acacia. This disease is an intermittent threat (Thu et al. 2010), and does not appear to have substantially reduced the overall productivity of acacia in Vietnam.

Fungal diseases that affect the leaves and branches of eucalypts have caused serious damage in some countries. In Thailand, thousands of hectares of clonal plantations were killed by an epidemic of *Cryptosporiopsis eucalypti* leaf blight fungus in 1 year (Luangviriyasaeng 2003). In central and southern Vietnam, large areas of *E. camaldulensis* plantations were lost to attack by leaf blight diseases, notably *Cylindrocladium quinqueseptatum* (Booth et al. 2000). Another leaf blight, *Kirramyces destructans*, has severely reduced productivity in Vietnam and Thailand (Dell et al. 2008).

Other diseases, such as the bacterial wilt *Ralstonia solanacearum,* appear sporadically and cause mortality in eucalypt plantations in China (Dell et al. 2008), but so far this has not become a major problem.

Insects and mammals

An insect of Australian origin, the eucalypt gall wasp *Leptocybe invasa*, was first observed attacking eucalypts in the Mediterranean Basin in 2000, and spread from there to Asia in less than a decade. Gall wasp has attacked eucalypt plantations in Laos, Vietnam, southern China and Thailand (Dell et al. 2008). It arrived overseas without the insect parasitoids that keep it under control in Australia, where it is not a pest (Mendel et al. 2004). It has caused severe damage to plantations in many countries (Dittrich-Schroder et al. 2012). Gall wasp infests the growing shoots and leaves, stunting new growth and preventing leaf expansion (Mendel et al. 2004). Severe attack will greatly reduce the canopy and lead to a reduction in wood production. It is reported that different eucalypt clones in Thailand vary in their susceptibility to attack (Vitoon Luangviriyasaeng pers. comm. 2012). This is consistent with the variation among species and clones demonstrated experimentally (Dittrich-Schroder et al. 2012). Biological control of this pest is discussed below. A range of other insect pests are found in most acacia and eucalypt plantations in SE Asia (Thu et al. 2010). However, other than gall wasp, most do not currently inflict major damage.

As noted in Section 4.1, monkeys are a significant pest of *A. mangium* plantations in some subregions of Sumatra, Indonesia. They ringbark the young trees while feeding on the sweet-tasting cambium and outer wood. This can kill trees outright, as well as creating wounds that form entry points for *Ceratocystis*.

Managing impacts of diseases and pests

Changing the genetics of the planting stock, by selection of resistant species/varieties and breeding, is an effective way to manage some pest and diseases. Approaches to this are described in Section 3.1.

Systematic estate-wide and regional surveillance is essential for detecting new incursions and to assess the severity and rate of spread of a threat. If a region has many smallholder plantation blocks, surveillance should cover them as well. In addition to planting genetically resistant stock, other management strategies include quarantine, chemical and biological control, and changes to stand management.

Surveillance

Effective surveillance gives early warning of the incursions and spread of diseases and pests. In view of the major economic importance of acacia and eucalypt plantations in the region and the current serious disease impacts on acacia plantations, there is a clear need for governments and the private forestry sector to develop coherent surveillance programs within and across national boundaries.

There is much that countries in the region can learn from their neighbours. For example, Vietnam can learn from the disease outbreaks in acacia plantations in Indonesia and Malaysia. A framework for joint surveillance, established with the support of governments, could enable collaborative research.

Quarantine

International quarantine regulations play key roles in containing or slowing the spread of diseases and pests around the world (Garnas et al. 2012). However, acacia and eucalypt plantations straddle the land borders between several SE Asian countries. The eucalypt gall wasp has spread from country to country within the last decade. Large volumes of logs are traded within the region (e.g. *A. mangium* logs with bark are transported from Malaysia to Vietnam) and could carry fungal diseases and insect pests. Within a country or its regions, quarantine regulations can also reduce the rate of spread. Nurseries have a particularly important role to play because, without good nursery hygiene, infected seedlings will be transported widely.

Chemical control

Pests or diseases in the nursery can be managed with appropriate chemicals. Chemical pesticides are seldom used in plantations, because of considerable environmental and cost impediments.

Leaf-cutter ants, which are serious pests of eucalypt plantations in Brazil, are controlled using an integrated pest management approach combining surveillance, genetic selection, and chemical control when required. The nests of leaf-cutter ants are treated and ant colonies are baited using chemical pesticides (Laranjeiro 1994). Outbreaks of defoliating caterpillars in eucalypt plantations in Brazil are sprayed with an insecticide derived from the bacterium *Bacillus thuringiensis* (Bt), as part of an integrated pest management approach.

Stand management

Stand management practices that increase the entry points for pathogens in trees can accelerate infestation rates. For example, spores of the *Ceratocystis* stem wilt/canker are carried from infected to uninfected trees by beetles, which are attracted to wounds on the stem or branches of acacia trees (Tarigan et al. 2011a). Experiments have shown that poor pruning techniques that damage the bark and expose wounds can increase the rate of spread of *Ceratosystis* in acacia plantations, compared with careful pruning (Tarigan et al. 2011b). Singling (pruning to produce a single leader) of young acacia plantations is no longer conducted by some companies in Sumatra. However, other agents (such as wind damage to stems and branches, bark stripping by mammals or infestations of stem-boring insects) create the conditions for disease spread (Tarigan et al. 2011a; Ploetz et al. 2013), destroying entire compartments.

Felling of infected trees and removing them off site can in some cases help to minimise the spread of pest or disease incursions, especially if coupled with regular surveillance. Removing stumps of acacia trees killed by root rot to reduce the pathogen load has been examined as a control measure. This operation is costly, causes soil disturbance and its effectiveness has been uneven (Eyles et al. 2008).

Biological control

Biological controls have been successful against some insect pests. Populations of some insect pests multiply and become threats when they reach exotic plantations that are free of their predators or parasites. Under these circumstances, biological control through the introduction of natural enemies has been effective. Control of the sirex wasp, *Sirex noctilio*, using parasitic nematodes imported from North America protects *Pinus radiata* plantations in Australia (Carnegie et al. 2005). Biological control using Australian insect parasitoids of the eucalypt gall wasp has been successfully developed and applied in Israel (Kim et al. 2008). Local parasitoid insect species, indigenous to the countries where wasp outbreaks occur, may also eventually control gall wasp to acceptable levels. They have been reported as attacking gall wasp in Israel and Turkey (Protasov et al. 2008), India (Kulkarni et al. 2010) and Thailand (Sangtongpraow and Charernsom 2013).

Biological controls for fungal diseases appear less promising. Some research is in progress to develop biological control of root rots (Mohammed et al. 2012; Eyles et al. 2013). *Trichoderma*, which is a fungal antagonist to *Ganoderma* root rot, is currently being tried in acacia plantations in Sumatra (Section 4.1).

Future success in dealing with the increasing threats of diseases and pests in SE Asia will require systematic and regular surveillance programs, well-managed quarantine regulations and a move towards integrated disease and pest management strategies, including a focus on breeding to improve resistance. In countries where plantations are managed by many small-scale growers and farmers who have no resources for surveillance and no training in pest and disease management, this is a challenge that can be addressed by partnerships between public and large-scale growers working towards national goals with the support of governments.

4 Country reports

4.1 Indonesia

In Indonesia, we focused primarily on *Acacia mangium* plantations on mineral soils in Sumatra. However, much of this resource is now being replaced by eucalypts, and we have extended the scope to cover early results of eucalypt productivity where data were available. For the reasons noted in Chapter 1, plantations on peat ecosystems are not considered here.

Indonesia introduced *A. mangium* (which is native to northern Australia and Papua New Guinea and West Papua, Indonesia) as a plantation species in 1979, first in Sumatra and later in Kalimantan. Large-scale planting of *A. mangium* has been in progress in Sumatra since 1990, and the area increased from 600,000 hectares in 1988–89 to 800,000 hectares in 2011. As the area converted from native forests on peat to plantations increased, *A. crassicarpa* (which is more tolerant to conditions in the low-lying areas of this ecosystem) became an important species, and its area has been expanding rapidly since 2000. Between 50–60% of the plantations managed by some large companies may be on peat in low-lying areas. Small-scale experimental plantings of a range of eucalypt species have been undertaken since the mid 1990s. *Eucalyptus pellita* and *E. urophylla* are the promising candidate species. Widespread and increasing stand mortality of *A. mangium* caused by diseases has since led growers to replace much or all of their *A. mangium* plantations with eucalypts.

First-rotation *A. mangium* plantations yielded 20–35 m^3 ha^{-1} y^{-1} in 8–10-year rotations. The species did not require much tending and was relatively free of pests and diseases. Encouraged by this, companies expanded *A. mangium* plantations with the expectation that they would be the primary source of pulp wood for several large pulp mills. Since early 2000, one mill has been fully reliant on plantation wood for pulping, while most others seem to have been accessing some of their wood from concessions permitted for conversion of secondary native forests to plantation forests or oil palm.

Most of the plantation resources in Sumatra are owned and managed by large companies, some of which own 200,000–300,000 hectares of land and are expanding their landholdings. Although some companies have attempted to foster smallholder plantations through various schemes, they have not gained much traction in Sumatra; unlike for example in Java, where smallholder plantations supply timber to many small- to medium-size wood-processing enterprises.

Breeding and deployment

Many of the first plantations of *A. mangium* were planted using seed from local seed production areas based on slower growing Queensland provenances of the species, and from seed collected from the wild. In the second rotation, growers increasingly used seed from seed orchards that were based on the best natural provenances in Papua New Guinea and adjacent areas of West Papua Province. Substantially faster growth of these improved seed sources in comparative trials is described in Section 3.1.

Attempts to develop clonal forestry with *A. mangium* and *A. crassicarpa* were not successful. The vigour of individual clones could not be maintained during the lengthy process of testing. However, one company has developed clonal family forestry for these species. Rather than direct planting in the field, seedlings from selected seed families from the seed orchards are used to produce multiple cuttings in the nursery, to bulk up the available planting stock of these families.

Genetic trials of *E. pellita* established that in the low-elevation environments of Sumatra, provenances from Papua New Guinea and West Papua grew better than Queensland provenances. Some growers now produce *E. pellita* seed from seed orchards based on these selected provenances (Hardiyanto 2003), and individual clones of *E. pellita* have been developed.

Probably over 80% of *E. pellita* plantations in Sumatra are clonal (E.B. Hardiyanto pers. comm. 2013).

Land use history and soils

Conversion of land to plantation forests and other plantation crops, notably oil palm, has a history of debate and conflict. Regardless of the history, large parts of the *A. mangium* plantations in Sumatra have been established on cleared secondary forests or on land dominated by alang-alang grass (*Imperata cylindrica*), which invaded degraded forests and sites that were cleared and burned for agriculture (Arisman and Hardiyanto 2006).

Landscapes are generally flat or gently undulating in much of southern Sumatra, but there is a higher proportion of hilly terrain in Riau province in central Sumatra. Sumatra has a humid tropical climate with long-term average rainfall ranging from 2,300 mm–3,600 mm y^{-1}. In South Sumatra, rainfall is seasonal with most rains falling between October and May, with a dry season from July to September. There is no distinct dry season in Riau province, although rainless periods are not uncommon. Year-to-year variation in rainfall is high, for example over the years 1991–2011 in the Subanjeriji region in South Sumatra province, annual rainfall varied from 1,800–3,580 mm y^{-1}.

Soils and their profiles vary. Mendham and Hardiyanto (2011) and Makruf Nurudin (pers. comm.) described the main soil types in South Sumatra plantation regions as Ultisols and Inceptisols. The former profiles are characterised by argillic horizons with a plinthite or haematite layer in the B horizon. The depth to this plinthite is now recognised to be a strong variable influencing growth rates. Plinthite is not a universal feature of soils under plantations in Sumatra. In Riau province the main soil types are Ferric Acrisols in the uplands, while in the lower valleys deep mixed riverine alluvium with very variable texture is common. Upland soils are widely planted and are yellowish-brown sandy clay to clay loam in the upper horizon, and brownish clay to more than 100 cm depth. Some of these soils are moderately consistent in blocky structure throughout. Surface soils in much of Sumatra generally have a moderate to high clay content ranging from 40–75%. Soil pH_{H20} tends to be uniform through the profile and may range from 3.6–4.2. Natural bulk density is usually in the range 1.2–1.3 g cm^{-3}, usually increasing to 1.2–1.4 g cm^{-3} at 50 cm. Soils are prone to compaction, especially if machines are allowed to operate when soil is wet.

Photos 1 and 3 show two typical profiles demonstrating soil depths and occurrence of plinthite in one case, and Photos 2 and 4 show the contrasting effects of these soil profiles on the growth of *A. mangium*. When grown at good sites, *A. mangium* will close canopy by the end of the first year. In contrast, on soils with depth to plinthite of about 60 cm, tree crowns are small and overall growth is poor.

Constraints on production, including diseases and pests

Companies in Indonesia have developed improved practices for managing *A. mangium* over the past decade. Improvements are notable in harvesting practices, inter-rotation management practices and in deploying genetically improved planting stock. Long-term experiments on productivity of successive crops show the potential for high rates of growth (Table 12).

In the study of Hardiyanto and Nambiar (2014),which was carried out in operational areas, wood volumes produced in second-rotation experimental stands were 33–39% higher than in the first-rotation operational stands. Second rotations at both sites took 2–3 years less to achieve the level of production harvested in the first rotation. Such improvements have come not from any single practice, but by sound inter-rotation management including harvesting without damaging sites, conserving organic matter, using genetically improved seedlings, improving weed control, and applying modest quantities of phosphorus (P) at planting. This study, and similar work in Riau province, Sumatra (Siregar et al. 2008), showed the importance of retaining site resources to maintain soil properties and support future growth. The natural pH of these soils is low, and in earlier years there was a widespread view that these soils were deficient in soil P. Well-designed field trials repeatedly show that the growth response to applied P may be significant at age 1 year or so (Mendham and Hardiyanto 2011) but, by the end of the rotation, benefit from P application tends to become small or nil. This leads to the conclusion that application of 5–10 g P per tree at planting would be adequate for the present, similar to the results from Vietnam (Section 4.3).

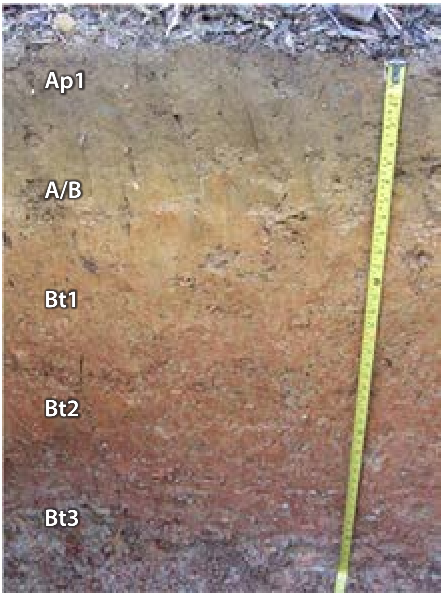

Photo 1. Soil profile with a plinthite layer at 40 cm

Photo 2. Corresponding tree growth is poor and canopy has not closed at age 1.5 years

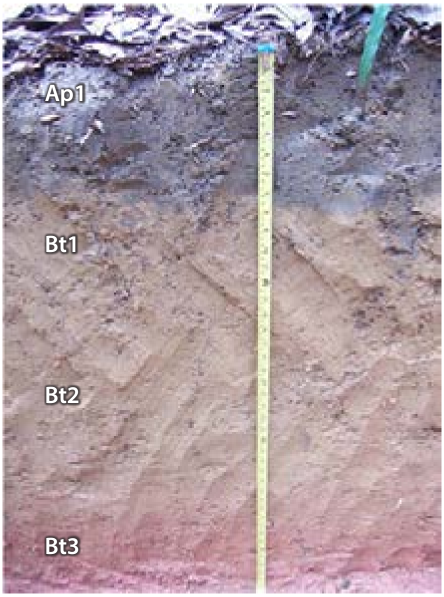

Photo 3. Deep profile with an Ap horizon high in organic matter

Photo 4. Corresponding stand is highly productive

Photos: Makruf Nurudin, in Mendham and Hardiyanto (2011)

However, retention of site organic matter, including bark wherever possible, is a key requirement for sustainable production. Section 3.2 reviews studies on *A. mangium* plantations that provide the information so managers can estimate the impacts of different harvesting intensities on site organic matter and nutrients, and thus guide their future decisions. Given proper management, there is no evidence of any significant decline in soil properties in the second rotation of *A. mangium* in Sumatra (Siregar et al. 2008; Hardiyanto and Nambiar 2014), except an indication of a reduction in extractable P (Section 3.4). However, only a modest application of P at planting is required in the second rotation (Mendham and Hardiyanto 2011). There has been little or no evidence of other nutrient deficiencies in *A. mangium* so far.

Despite the significant progress achieved over the last decade in plantation management, the future of *A. mangium* plantations in Sumatra is uncertain. Two major diseases, root rot (*Ganoderma* sp.) and stem wilt/canker (*Ceratocystis* sp.), are now causing levels of mortality so high that a significant proportion of these plantations are no longer viable. Evaluation of the incidence of root rot suggests that build-up of inoculum is increasing with successive rotations (Potter et al. 2006; Mohammed et al. 2012). In one study at a second-rotation site, retention of a high level of slash increased the incidence of root rot (Siregar et al. 2008). Practices such as stump removal to reduce inoculum have given mixed results in field experiments. Several companies are screening for tolerant genetic material, but it will be some years before their outcomes are clear. Research on biological control of *Ganoderma* is also in progress. A number of studies have found promising early results using endophytic *Trichoderma*, some isolates showing higher effectiveness than others

Table 12. Productivity in the first and second successive rotations of *A. mangium* plantations in South Sumatra, Indonesia

Site	Rotation	Rotation age (year)	Volume (m^3 ha^{-1})	MAI (m^3 ha^{-1} y^{-1})
Toman	First	9	265	29.4
	Second	6	258	43.0
Sodong	First	10	297	29.7
	Second	7	335	47.8

Source: Hardiyanto and Nambiar (2014)

Photo 5. Mechanical harvesting operation in South Sumatra—by travelling over the retained slash layer and by orderly stacking of cut-length logs, this practice would leave little or no damage to soil. Photo: E.B. Hardiyanto`

Photo 6. Mechanical harvesting operation in Riau, Sumatra—slash is redistributed after log processing. Groups of whole trees are brought in and processed close to the road. When the machine returns to pick up the next batch of trees it carries slash back to the stumps and redistributes it.

(personal communications from company R&D to S. Nambiar during field visits). Some of these isolates have already been deployed operationally with the expectation that even small improvements, if realised, are worthwhile. There have been no regulations for controlling the movement of machines that carry soil in their tyres from disease-infested to disease-free areas and, partly because of this, root rot is now endemic in most areas.

Outbreaks of *Ceratocystis* stem wilt/canker have been more damaging than root rot, although *Ceratocystis* was recognised as a major problem later. The spread of *Ceratocystis* is aggravated by bark peeling and stem wounding by squirrels, monkeys and elephants, especially in compartments close to retained native vegetation, resulting in severe damage to plantations. *Ceratocystis* fungal spores are carried by beetles that burrow into the bark of trees carrying the infection. Thus, spread of this disease is accelerated by multiple agents, making disease management difficult. There is some research underway aiming to find genetic variation in disease tolerance.

In some subregions, monkeys are a serious pest of *A. mangium*. In addition to their role in the spread of *Ceratocystis*, monkeys have directly destroyed some 30,000 hectares of plantations by ring-barking young trees, in the process of feeding on the sweet-tasting cambial wood.

Incidence of heart rot disease in *A. mangium* has received attention (Siregar et al. 2008) but this disease is now not considered as a significant threat to short-rotation forestry for pulpwood production. Incidence seems higher in older trees with ages beyond the harvesting regime in practice.

Currently, the only solution to deal with the twin problems of root rot and *Ceratocystis* is to shift from *A. mangium* to eucalypts, and this transition is now in progress at various rates by different companies. In general, productivity of eucalypts planted during the past decade has been lower than that of *A. mangium* (see Chapter 5) but it is likely that with improved knowledge and application, productivity can be increased. Eucalypts are not immune to root rot fungi and *Ceratocystis* (Roux and Wingfield 2009; Guimaraes et al. 2010) but appear to be less susceptible than *A. mangium*. Nevertheless, as the area under eucalypts increases, and given the lack of regulation in movement of machines and vehicles within the estates, disease problems may increase for eucalypts. This is an area requiring close monitoring and attention.

Research priorities

Site, soil and landscape factors determining productivity in space and time

In Chapter 5, the high variation in productivity across plantation landscapes, based on preharvest inventory (Chapter 5, Figures 12–15), is discussed. Companies use inventory data only for stocktaking of standing wood, when in fact it can and should be used as biologically important spatial and temporal information. None of the inventory databases have yet been used to understand the pattern of spatial variability and the biophysical attributes (soils, terrain, genetics and management) which drive production. None of the companies have established reliable quantitative relationships linking soil attributes and

Photo 7. Symptoms of *Ganoderma* root rot on *A. mangium*. Photo: E.B. Hardiyanto.

Photo 8. Symptoms of *Ceratocystis* on *A. mangium*. Photo: E.B. Hardiyanto

growth rates. In the absence of such basic information, prescriptions of 'site-specific standard operational procedures' have low reliability. These issues are equally important for both acacias and eucalypts and for mineral and peat ecosystems. Because this is not recognised, inventory data collected at high cost remain undervalued and underutilised beyond their immediate application to estimate current wood flows.

A significant and focused investment in understanding and modelling spatial and temporal dynamics of production would aid future management and R&D investment decisions.

Assessment of genetic gain at operational level from rolling deployment of improved genotypes

Companies have active breeding programs for acacias and eucalypts. We will not comment on the detail of these programs here; breeding is reviewed in Section 3.1.

Strong links between inventory systems and breeding programs can enhance breeding progress. Ultimately, realised improvement in productivity in operational plantings is the primary goal of breeding. Information on the performance of clones and seedlots linked to local site characteristics, obtained from many inventory plots across the plantation estate, is of great value for breeders and will complement results from formal genetic trials.

Judicious management of vegetation

Herbicide technology is widely applied in Indonesia and, without it, commercial wood production would not be achieved. However, the operational practice aimed at implementing a 'zero weed tolerance' policy practised by some companies is not based on sound experimental evidence. This idea has been carried over from experience in oil palm and rubber plantations. It is unlikely to be relevant for forest ecosystems, nor in tune with contemporary views on vegetation management in forestry that promote optimum vegetation management balancing productivity and understorey development. The prevailing thinking seems to be to further increase the intensity of herbicide application for eucalypt plantations, on the belief that they are more sensitive to competition by weeds than acacias are. It is true that eucalypts will seldom achieve and maintain high leaf area like *A. mangium* and weed growth may be higher under their more open canopies, but it is possible to develop cost-efficient and environmentally superior management regimes that do not involve elimination of all understorey vegetation.

Research aimed at rationalising vegetation management strategy to refine technology to reduce production costs, lessen the dependence on scarce labour and reduce environmental impact, is likely to return good dividends.

Management of diseases

The urgency arising from the threat of diseases has already been discussed. Coordinated research is required at various levels:

Long-term research (e.g. discovery of resistant and locally adapted germplasm and robust biological control programs) for managing the adverse impacts of both *Ganoderma* and *Ceratocystis* is essential.

It is important to establish if there are relationships between site factors and *Ganoderma* incidence. This would be a prerequisite for developing criteria for determining the areas of low and high risks and potential management approaches to contain the disease. Need for this has been recognised for several years but R&D efforts have not yet found any relationship linking site/soil properties to *Ganoderma* incidence.

Comparative studies on the productivity of A. mangium *and eucalypts, especially defining the management regime for improving eucalypt productivity*

Although a large body of information on the productivity of eucalypts in short rotations is available from countries including Brazil (mostly subtropics, but including some wet equatorial lowland sites), Australia (temperate Mediterranean) and South Africa (seasonally dry subtropics), experience in managing highly productive systems in the equatorial humid tropics is limited. Almost certainly, new challenges to production, including new threats from pests and diseases, will emerge.

Eucalypts are being planted at sites that were under one or two rotations of *A. mangium*, which should have improved the nitrogen (N) capital at these sites. This has been difficult to establish with measurements of total soil N (Siregar et al. 2008; Hardiyanto and Nambiar 2014), although studies with isotopes of N in Sumatra have shown N gains in the range of 150–200 kg N ha^{-1} during the first 18 months of the second *A. mangium* rotation (Wibisono and Mendham pers. comm. 2013). However, several current experiments in Sumatra with *E. pellita* and other eucalypt clones show noticeable early growth response to addition of N in fertilisers. Clearly, successive rotations of eucalypts, which do not fix N, would differ in their N budgets. Thus, the effects of site conversion and management of eucalypts (especially the N dynamics) will require significant research.

Studies integrating different aspects of production management, with medium-term goals, are a first priority. Core elements should include: assessing productivity at the landscape level; relationships between site/soil factors and growth; pest and disease management; methods for managing the N economy; and N efficiency of eucalypt plantations.

4.2 Sabah, Malaysia

Plantation forestry in Sabah commenced in the 1970s. Timber from short-rotation plantations was expected to provide wood supplementing the log harvests from natural forests. Plantations were established on clear-cut forest sites, and on *Imperata* grasslands. Some plantation blocks are now into the fourth rotation, making them of particular interest to our study. We visited two of the largest plantation growers, one of which manages an estate of 50,000 hectares (31,000 hectares of *A. mangium* and 19,000 hectares of eucalypts), and the other approximately 25,000 hectares of which 18,000 hectares is *A. mangium*.

Breeding and deployment

During the early development of plantation forestry, several species from different genera were planted. Very few blocks of *Pinus caribaea* or *E. deglupta* grew at an MAI higher than 5 m^3 ha^{-1} y^{-1}. The average growth rates of *Gmelina arborea* were 10 m^3 ha^{-1} y^{-1}or less. *Paraseriathes falcataria* is still grown on short rotations for sawlogs, growing in the range 10–14 m^3 ha^{-1} y^{-1} on third- and fourth-rotation sites. *Acacia mangium* is now the dominant species. Companies are planting *A. mangium* raised from seed orchards with Papua New Guinea provenances. There are small areas of clonal acacia hybrid and *A. crassicarpa* plantations.

Eucalyptus grandis and *E. urophylla* are planted at sites with elevations above 800 m. More recently, in response to disease threats to *A. mangium*, small areas of *E. pellita* have been planted on lower elevation sites.

Diseases and pests

Mortality in *A. mangium* in patches attributed to *Ganoderma* spp. has been a significant problem. The emergence of *Ceratocystis acaciivora* stem wilt/canker since 2010 is a serious cause of tree mortality, as it is in Sumatra. In some cases, entire plantation blocks have died. As in Sumatra, spread of *Ceratocystis* is accelerated by bark peeling by squirrels, monkeys and elephants. No control measures are yet in sight. One grower is replacing *A. mangium* with *E. pellita* and this may be required at a faster pace.

Landscape and soils

In Sabah, plantations are predominantly on steep and undulating hillsides, with dissected terrain and slopes often exceeding 20°. Most, if not all, of these lands were under native forest. Soil types vary. Some are Haplic Acrisols (FAO) developed on sandstones and shales, with surface soil texture ranging from sandy clay loam to clay loam extending to massive argillic B_t horizon (Ilstedt et al. 2004). There are also large areas of Gleyic Podzol and Orthic Acrisol (Sim and Nykvist 1991) and red-yellow Podzols. Several of these soil types are likely to have high levels of exchangeable aluminium and low organic matter content especially in the A/E and B_t horizons, and if they are exposed by displacing the surface soil during mechanised harvesting operations (Photo 9), the soil may become increasingly P-fixing and difficult to amend in the future.

The high rainfall of 2,500–3,500 mm per year, the steep terrain, and soil types impose high risks for plantation management in these landscapes. To prevent deterioration of site quality through soil erosion and compaction, careful planning and implementation of successive cycles of plantation establishment and harvesting are essential.

Site and stand management across rotations

Heavy clay soils are easily damaged by snig tracks. When exposed, these laterised soils showed evidence of rapid oxidation, changing in colour from yellow-brown to reddish-brown concretions. They will have high P-fixing capacity. Restoration is difficult especially when there is indiscriminate vehicle movement within sites, resulting in extensive soil exposure and damage associated with mechanised harvesting.

We found that plantation harvesting and subsequent re-establishment are often poorly coordinated. Snig tracks proliferate through the harvested blocks in an unplanned way. Mapping (using GIS systems) of the layout of permitted traffic routes in compartments will enable re-entry on the same tracks in successive rotations. At present, with no such record, tracks soon become overgrown and new tracks may be cut in successive harvests, progressively expanding the proportion of heavily disturbed soil within compartments and thus loss of productive growing area. One grower has moved to cable logging that promises to reduce soil disturbance and compaction, while other growers continue with tractor harvesting.

Weed control was manual in the first rotation. There is still reliance on immigrant labour for weeding and this is bound to be a problem in the long term. Growers are now moving to the use of herbicides. Logging slash is no longer burned. Fertilisers are applied once at planting.

Productivity of *A. mangium* plantations has suffered significantly in recent years in parts of Sabah. Some have failed, due to the combined impacts of diseases and weed growth. Site degradation inflicted by poor harvesting techniques has contributed to reduced growth in some instances.

Photo 9. Bark stripped by elephants from 5-year-old *A. mangium* trees

Photo 10. Symptoms of *Ceratocystis* infection in 2-year-old *A. mangium* trees

Photo 11. Snig track with adjacent soil showing heavy disturbance from mechanical harvesting

Photo 12. Recently logged *A. mangium* plantations in hilly terrain

Research priorities

Disease management

Efforts have commenced to screen *A. mangium* germplasm to find genotypes tolerant to *Ceratocystis*. Early indications suggest that this will not be easy and much work may be required (J. Brawner pers. comm. 2013).

Screening and breeding of acacia and eucalypt germplasm for disease tolerance is a high-priority activity. While changes to stand management (e.g. minimising stem wounding from weed control and singling operations and reducing impacts of browsing animals) might reduce the rate of spread of *Ceratocystis* disease, acacias may need to be abandoned as plantation species in Sabah within the next decade, unless tolerant acacia germplasm can be identified and mass-propagated for planting. Meanwhile, pest and disease challenges for *E. pellita* and other replacement species will undoubtedly emerge, and research must investigate these new challenges.

Redesign of harvesting systems

The combination of steep terrain, soils with high clay content and intense almost year-round rainfall make harvesting decisions in Sabah complex, yet it is also a region in which environmentally sound harvesting practices are critical for sustainable forestry. The importance of this has been well demonstrated by previous research in the region (Sim and Nykvist 1991; Panitz and Adzmi 1992; Ilstedt et al. 2004).

A revised harvesting code-of-practice which optimises the network of roads and snig tracks mapped on a GIS platform so they will form the template for subsequent harvests, would help to minimise soil damage and erosion. This needs to be implemented with appropriate training of harvest contractors and operators on all aspects including risk-evaluation techniques. Harvesting systems should be developed and implemented as part of the site preparation for planting. Cable harvesting needs to be used on more of the land base where slopes exceed 20°.

Integrated management systems

As reported in Chapter 5, acacia plantations have high variability in growth at small scales and ongoing mortality as the rotation progresses, even in the absence of disease.

Research to better understand the causes of mortality, and improve management to maximise survival, is key to lifting wood production.

Attention to minimising soil compaction, effective weed control using careful herbicide regimes, and moving to use of best-available improved genetic material has clearly paid dividends, as indicated by recent increases in early growth rates of *A. mangium* to age 3 years (Table 15). But more attention needs to be given to whole-of-system thinking rather than seeing genetics, harvesting, site management and nutrition as separate research areas.

Work is in progress on testing *E. pellita* as a potential replacement for *A. mangium*. However, changing to *E. pellita* will require major modifications in plantation management, particularly with respect to ground vegetation and nutritional management. Adaptive research is needed to improve management of the new species.

Use of inventory systems for understanding productivity in space and time, and as a research tool

Plantation inventory data can be better integrated with company R&D effort. For example, the system of inventory plots can be used for pest and disease surveillance as well as growth monitoring, rather than having to manage a separate surveillance network.

Simple experiments can be set up within the network of inventory plots to evaluate, for example, alternative nutritional and vegetation management treatments across many paired plots. This may provide information more applicable to management than would be obtained from one or two large experiments that may not be representative and are hard to establish in a highly variable terrain.

4.3 Vietnam

In Vietnam, the area of forest plantations has expanded rapidly during the past two decades. The Directorate of Forestry estimates that in 2013 the total area of acacia plantations was 1.1 million hectares, with 600,000 hectares of *A. mangium*, 400,000 hectares of clonal acacia hybrid (*A. mangium* × *auriculiformis*), 90,000 hectares of *A. auriculiformis,* and 5,000 hectares of *A. crassicarpa*. The most rapid expansion has been of *A. mangium* in the north. Some of the current acacia plantations were previously under eucalypts. The area of eucalypts is probably about 200,000 hectares, with many additional row plantings and scattered trees along roads, canals, and farm and home boundaries in the rural landscapes. The most important eucalypt species are *E. urophylla* and *E. camaldulensis*, although some interspecific hybrid clones have also been planted.

Our study focused on the productivity and management of acacia plantations that, together with the export and processing industries that depend on them, are major contributors to the national economy. In 2011, about 4.5 million dry tonnes of acacia woodchips, equivalent to about 9 million cubic metres of pulpwood, was exported to other Asian countries for the production of kraft pulp. Two local pulp mills, at Bai Bang in Phu Tho province and An Hoa in Tuyen Quang province, each produce about 120,000 tonnes of pulp per year. This equates to about 1.2 million cubic metres of pulpwood, much of which is acacia, although these mills use a proportion of eucalypt wood. Fibreboard mills are also significant consumers of small-diameter acacia wood. Many sawmills produce sawn boards from small acacia logs in the diameter range 12–25 cm. The most important use of sawn wood is furniture manufacture.

Ownership and management arrangements of plantations in the country are complex. The Ministry of Agriculture and Rural Development (MARD 2011) estimates that about 50% of the land area under plantations has been allocated to individual households, which are typically allocated less than 5 hectares of plantation land. Most of the balance of the plantation estate is managed by local management boards, people's committees and state forest enterprises. Individual forest enterprises and private companies seldom directly manage more than 5,000 hectares of plantations. Some of them enter into joint ventures with local or overseas private companies, and they often give technical assistance to and co-invest with nearby household growers under a range of contractual arrangements, in return for a share of the wood harvest.

Many of the larger growers use inventory systems to assess volume production (Chapter 5). Farmer households do not. As described by Blyth and Son (2014), many household growers sell trees on the stump to harvesting contractors, who pay based on an estimate of standing volume. Some smallholders harvest and transport their wood for purchase by wood merchants at the roadside.

Photo 13. A smallholder plantation of a hybrid acacia on hilly terrain in central Vietnam. Site preparation, planting and weed control are all manual

Breeding and deployment

The Institute of Forest Tree Improvement and Biotechnology (IFTIB, formerly the Research Centre for Forest Tree Improvement) has led the work in breeding and deploying genetically improved acacia planting stock. Species and provenance testing identified *A. mangium*, *A. auriculiformis* and *A. crassicarpa* as the most promising species. Breeding populations of *A. mangium* and *A. auriculiformis* were established in the mid 1990s and second-generation progeny trials of these species were established in 2008. Breeding of *A. crassicarpa* commenced later but has now reached a similar stage. Seed production areas and seed orchards are managed by IFTIB, but they have not been able to provide sufficient seed at prices acceptable to many growers. Some plantations continue to be established from seeds collected from commercial plantations of *A. mangium* and *A. auriculiformis* or from imported seeds of selected natural provenances of *A. mangium*. The development of clonal forestry with the *A. mangium* × *A. auriculiformis* hybrid (Kha et al. 2012) has been a major achievement. In 2000, six tested hybrid clones were certified by MARD for distribution. By 2008, a further 11 hybrid clones had been certified, but to date only about six clones are planted on a commercial scale. Plantations are established as a mix of several different clones rather than as mono-clonal blocks. Clones of *A. auriculiformis* displaying good vigour and stem form have also been certified by MARD. Technology and systems for clonal acacia nurseries to produce low-cost planting stock of these clones were developed by IFTIB and clonal nurseries have been established in most provinces. The genetic base of acacia hybrid breeding has now been expanded and many new hybrid clones are now under evaluation.

Tissue culture is essential to support acacia clonal forestry. Plants used to establish clone hedges adjacent to nurseries are derived from tissue-cultured plantlets rather than by serial cutting propagation, to avoid the risk of ageing and the loss of rooting ability. Clones of *A. auriculiformis* and acacia hybrid can be periodically returned to tissue culture from young, vigorously growing ramets. The first hybrid clones, selected in 1991, remain vigorous 20 years after their initial deployment (Kha et al. 2012). However, clones of *A. mangium* and *A. crassicarpa* have not been developed; they lose rooting vigour before clonal testing can be completed. Clonal family forestry to mass-multiply seed families is now under evaluation. This would enable large-scale deployment of the best family seedlots from IFTIB's breeding program.

Diseases

In Vietnam, acacia plantations remain relatively free of major pests and diseases, in contrast to the current situation in Indonesia and Sabah. Some outbreaks of pink disease (*Corticium salmonicolor*) have led to salvage harvesting and loss in production. According to local information, this disease is more severe in seasons when rainfall is higher than normal. In severe outbreaks, mortality can be 70–80%. Stem cankers caused by fungal pathogens such as *Botryosphaera* spp. are a concern, particularly for sawlog growers. *Ceratocystis* has been identified in Vietnam (Dr PQ Thu, Vietnamese Academy of Forest Sciences, pers. comm. 2013) and it should be treated as a serious threat to the resource.

Soils

Acacia and eucalypt plantations and woodlots are grown on a wide range of soils and terrain including:

- reddish-yellow Ferralsols in the mountainous land in northern and central Vietnam
- grey-brownish Chromic Acrisols on old alluvial deposits in the south
- deep siliceous costal dune sand
- acid sulfate soils in the low-lying Mekong Delta in the south.

Productivity in large parts of these plantations is low and variable. This is partly due to soil properties and partly to inappropriate management practices. Little quantitative information is available relating to soils and productivity for acacia and eucalypts in Vietnam, apart from very general descriptions. However, Do Dinh Sam (2001) provided a general summary. Examples given show the overwhelming importance of soil depth (rooting volume) on growth rates. The MAI of *A. mangium* on sites with soil depths of ≤50, 80 and ≥ 100 cm were 6, 16 and 26 $m^3\ ha^{-1}\ y^{-1}$, respectively. Similarly, in the south where soils are generally alluvial in origin, the growth rates of *A. auriculiformis* ranged from 6–10 $m^3\ ha^{-1}\ y^{-1}$ in shallow soils to 22–24 $m^3\ ha^{-1}\ y^{-1}$ in deeper soils.

Two profiles within the Acrisol soil group are shown in Photos 16 and 17. The profile in Photo 16 is deep, with sandy clay loam in the A horizon to sandy clay extending to layers deeper than 120 cm. The profile in Photo 17 has a similar A horizon as in Photo 20, but from 40 cm in the B horizon the profile contains laterised gravel which increases with depth occupying 60–70% of the soil volume. These two sites are located nearby, receiving the same annual rainfall, but the amounts of soil water determined by the depth of soils and rooting volume will be very different, and this has significant impacts on growth rates during the 4-month dry season. Any loss of surface soil due to forest management practices would have serious adverse effects on productivity. Large areas currently under plantations in central Vietnam are on eroded soils containing large amounts of gravel. Retention of organic matter and judicious management of competing vegetation are the two ways to improve available water to trees.

Management practices

Many sites have been through two full cycles of plantation establishment and harvest. Management practices vary according to ownership and location of plantations. Many smallholder plantations, smaller than 5 hectares, are located in steep, hilly terrain, or on small hills isolated amongst surrounding agricultural crops. Under such conditions, all site preparation and planting is manual. Slash and existing vegetation are, in most cases, burned before planting. Weed control is by hand, with circle weeding around trees twice yearly for the first 2 years after planting. This retains a diverse ground vegetation cover.

Photo 14. Stem canker on a 6-year-old tree in clonal plantation of *A. auriculiformis*, southern Vietnam. Note excellent stem form of clonal planting stock

Photo 15. Careless pruning of this young acacia hybrid tree, carried out to reduce the chance of stem breakage from typhoons, has stripped the bark and exposed the tree to attack by pests and diseases

Photo 16. Soil profile from Phu Binh, southern Vietnam, with deep, sandy clay loam. Photo: Forest Science Institute of South Vietnam

Photo 17. Soil profile from Phu Binh, southern Vietnam, containing laterised gravel. Photo: Forest Science Institute of South Vietnam

Many plantations managed by public and private growers are located on less steep, moderate to gently undulating landscapes or in flat alluvial areas in southern and central Vietnam. A number of current practices have the potential to degrade these sites in several ways. These include:

- bulldozing to clear ('clean') the site after harvest, often on slope, giving rise to complete removal of above-ground biomass and stumps from the previous rotation (Photos 18 and 19)
- exposing bare soil that initiates severe soil erosion (Photos 18 and 19)
- ploughing before planting and once or twice per year for 1–3 years after planting to control weeds and to reduce the vegetation fuel load to prevent fire outbreaks. Repeated ploughing has caused loss of soil structure, soil displacement, and poor drainage leading to surface flow (run-off) in some soils (Photos 20 and 21)
- in some cases, leaves and twigs are sold for fuel, leaving the soil surface bare and exposed for several months.

Thus, the advantages of manual harvesting for the site are lost through subsequent site management.

Fertiliser doses are usually moderate, with 100 g or 200 g of a mixture containing N, Pand K applied in the planting hole. Composted animal manure or organic fertilisers are often added. These applications would not replace the losses incurred by displacement and loss of organic matter and surface soils resulting from the practices described above.

Research highlights relevant to site management

Vietnam has a long history of research on introduction of tree species, their domestication and breeding, described earlier in this section. Long-term studies on site management and sustainable production in acacias commenced in 2000, largely in collaboration with CSIRO but also as a partner (2002–08) in the CIFOR network study (Nambiar 2008). In one study (Huong et al. 2008) which is still in progress, the productivity of *A. auriculiformis* plantations is being studied for three successive rotations at the same site in southern Vietnam. Figure 11 shows the MAI of three rotations. The first rotation (1R) was an area within a commercial stand (planted in 1995 and harvested in 2002). The second rotation was established soon after harvest as an experimental stand (2R) with a range of contrasting management treatments and was harvested in 2008. The third (3R) experiment is due for harvest in 2014 at age 6 years.

The MAI for 2R (full rotation at age 6 years) and 3R (at age 4 years) are the means of contrasting management treatments. The results showed that the increase in productivity from 1R to 2R was nearly threefold and that the rates of growth are being maintained or improved in the third rotation. At the end of the rotation, the above-ground biomass of 1R was 56.6 t ha^{-1} compared to 111.8 t ha^{-1} in 2R. These productivity gains have been realised through the complementary effects of genetically improved

Photo 18. Gully and surface erosion after harvesting the stand and then clearing slash, litter and stumps by bulldozer, followed by heavy rain, central Vietnam

Photo 19. Slash and litter bulldozed into streamlines to 'tidy' the planting site. Note the loss of surface soil

planting stock, conservation of site organic matter and weed control, which improved survival. Lasting benefits from application of P fertiliser have been small. Important changes have occurred in the soil. In the top 0–10 cm, soil organic carbon (SOC) increased from 16.7 g kg^{-1} at the end of 1R to 21.2 g kg^{-1} at the end of 2R with corresponding increases in soil N from 1.1 g kg^{-1} to 1.6 g kg^{-1}. Extractable P declined from 8.7 mg kg^{-1} to 5.4 mg kg^{-1} during the second rotation (Huong et al. 2008; Huong pers. comm. 2013).

Photo 20. Inter-row ploughing in acacia hybrid plantation, SE Vietnam. Note surface erosion, and failure to control weeds along planting rows. Repeated discing with heavy discs move soil towards tree rows, deepening the inter-rows

Photo 21. Ploughing here has led to the slicing of clay soil into glazed, hardened blocks in which root penetration could be difficult

In a related trial, the degree of weed control required to achieve good growth was studied. Treatments were:

- C0: control (one pre-planting herbicide applied and no further weed control)
- C1: 1.5 m wide strip centred on tree rows kept weed-free with herbicide application as required
- C2: entire plot kept weed-free by herbicide application throughout.

At age 6 years, wood volumes were C0: 110 m^3 ha^{-1}, C1: 168 m^3 ha^{-1} and C2: 179 m^3 ha^{-1} (Forest Science Institute of South Vietnam, unpublished data 2012). The difference between strip weed management and the zero weed regime was small. Under strip weed control, native understorey vegetation established between tree rows, with no negative impacts on tree growth. Although results for one site cannot be generalised, it does show that there is much scope for further research in judicious management of vegetation in plantations without resorting to a 'zero weed' approach or repeated ploughing of the inter-rows.

A second trial was established at Dong Ha in central Vietnam (Dinh et al. 2010), on a heavily disturbed hillside site with a gravelly, shallow soil where the A horizon had been lost to erosion under previous land use. Productivity of the first rotation of acacia hybrid, harvested in 2007 at age 9 years, was 19 m^3 ha^{-1} y^{-1}. After harvest, all slash was left to decompose on site and there was no burning. The acacia hybrid planting stock in the second rotation used a mix of six clones: three planted in the first rotation, and three new ones. The experimental site had a slope

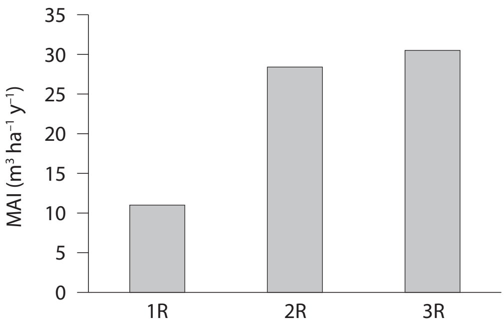

Figure 11 Productivity of three successive rotations of *A. auriculiformis* at Phu Binh, southern Vietnam. Source: Forest Science Institute of South Vietnam internal report

of about 10–15°. To account for any slope effect, four replicates, each testing five experimental treatments, were laid out down the slope, over a total downslope distance of 200 m. The mean productivity across the experiment at age 5 years was 20 m^3 ha^{-1} y^{-1}, nearly the same as that in the first rotation.

Of particular interest was the productivity trend represented by the replicates. The replicate means increased downslope from 16.5 m^3 ha^1 y^{-1} at the top of the experiment, followed by 16.7, 22.0 and 25.0 m^3 ha^{-1} y^{-1} towards the foot of the slope. Soil organic carbon and N in the surface 10 cm of soil increased down slope in parallel to this trend of increasing productivity. These trends in growth rates, SOC and N may, to some extent at least, be associated with downslope movement of surface soil under previous land use. They point to the importance of understanding spatial variation in site productivity

Photo 22. Dong Ha, central Vietnam, experimental site before establishment of the second rotation, looking down slope from the uppermost replicate. After harvest, all slash and litter was retained before replanting.

Photo 23. Dong Ha second-rotation acacia hybrid experimental plantation at age 5 years. An understorey has developed after four herbicide applications in the first 2 years after planting.

Photo 24. Phu Binh third-rotation *A. auriculiformis* experimental plantation at age 4 years, with weed control by judicious herbicide application. An understorey has developed in this productive plantation.

when interpreting experimental trials and yields from operational plantations. In this experiment, the slope position effect on productivity was much greater than the impact of P fertiliser applied at planting, compared with unfertilised control treatments.

Although there are few well-designed nutrient application experiments in Vietnam, available results point to only a modest growth response of acacias to P. An application of 5–10 g elemental P per tree at planting seems adequate for a full rotation (Huong et al. 2008; Harwood, unpublished data). However, soil-extractable P has shown a gradual decline from planting during the second rotation at the Phu Binh site, despite significant amounts of P being returned in litter fall (Forest Science Institute of South Vietnam, unpublished data) that suggests the need for a closer examination of the dynamics of P in acacia plantations. Such investments are also likely to be useful for improving the management of eucalypt plantations, which will also require close attention to N nutrition. Application of Ca and K has not produced growth responses in acacia to date.

Research priorities

Integrated approach for managing the risks from diseases, pests and climate

Vietnam has already developed genetically improved acacia varieties for the different lowland environments and has the capacity to achieve ongoing improvement. The disease problems encountered with *A. mangium* in Indonesia and Malaysia should be taken as a serious warning for acacia plantation sustainability in Vietnam. Typhoons are another threat causing severe damage to plantations particularly in central Vietnam.

Future breeding should focus on improving pest and disease resistance. Parallel to this, stand management practices need improvement to reduce the risk of disease spread. A change in practice is required to reduce stem wounding from careless pruning. Vietnam urgently needs to invest more in pest and disease surveillance of acacia and eucalypt plantations to enable detection and containment of outbreaks. Effective external and internal quarantine regulations could minimise the movements of pests and diseases and reduce future risks. Improving wind tolerance should also be taken into account in breeding.

Sustainable management

Productivity of acacia plantations in both degraded stony soils and moderately fertile alluvial soils can be improved substantially by proper inter-rotation management practices, with conservation of site resources being central. Nevertheless, many growers currently use undesirable management practices such as burning/removal of logging slash and repeated ploughing for weed control.

Research on contemporary methods of vegetation management should address issues of improving production and also ways of reducing the risk of fire damage to plantations, working with neighbouring communities to reduce the incidence of fire and improve fire suppression.

A participatory research program involving leading growers is warranted that will develop better site and stand management practices and will also serve as demonstration at sufficient scale. A R&D cooperative coordinated by the Vietnamese Academy of Forest Sciences, but with joint investment and co-management by growers, may be a way of achieving efficient and cost-effective R&D.

Research to support small growers

Plantation management systems suitable for companies with large areas in relatively level terrain and resources for mechanised site management will not be appropriate for poor smallholder families with 1–2 hectares of plantation on steep terrain. This is an especially important issue for Vietnam because nearly half of the country's total plantation area is managed by smallholders, yet the organisation of research and development is not structured to support them and there is little contact between researchers and smallholder growers. Access by small growers to genetically improved planting stock, especially high-quality seed of *A. mangium,* is another important issue.

Research on plantation management specifically targeted to the needs of smallholder growers needs to be undertaken. One clear research priority is developing improved inter-rotation management systems including vegetation control for increasing production and preventing fire. Vietnam should also invest in researching and developing effective learning systems for smallholders to help them adopt improved management practices, taking into account their needs and their access to technology.

4.4 China

China has the world's third-largest eucalypt plantation estate. The latest estimates (August 2013) indicate a total of over 4 million hectares, of which about 2 million hectares are in Guangxi province and 1.35 million hectares in Guangdong province (Xie Yaojian, China Eucalypt Research Centre, pers. comm. 2013).

The market for eucalypt wood in China is currently very strong, buoyed by the development of rotary veneering and plywood industries that use eucalypt logs 8–15 cm in diameter grown on 5-year rotations (Arnold et al. 2013), as well as the increasing demand for pulpwood and small-diameter wood for the production of medium-density fibreboard (MDF).

We visited seven companies responsible for managing in total about 1 million hectares of eucalypt plantations in Guangxi and Guangdong provinces. Some of them provided data on productivity from inventories (Chapter 5).

In the section below, we offer observations that are relevant to sustainability. Each of these is neither universal nor applicable to the land managed by all growers visited, but neither are they isolated situations or practices. They are important enough to warrant attention.

Breeding and deployment

Most plantations in Guangxi and Guangdong provinces are now based on clones of interspecific hybrids. *Eucalyptus urophylla* × *grandis* is the most commonly planted taxon, but clones of other hybrid combinations are also planted. The *Eucalyptus urophylla* × *tereticornis* hybrid is prominent in coastal locations prone to typhoons because of its resistance to wind damage. Individual clones are planted in monoclonal blocks typically 1–10 hectares in area. The plantation landscape typically comprises a patchwork of different clones. Most companies have deployed fewer than five clones across their estates. This exposes them to high risk of failure, if a widely planted clone becomes susceptible to pests or diseases. However, the number of clones planted is increasing, as more clones are developed through company breeding programs and by the China Eucalypt Breeding Alliance. Most of the growers who contributed to this review are members of this alliance. Genetic gains will accrue to members through testing and reselection of existing clones in the short term and through pure-species and hybrid breeding, and testing and release of resulting new clones in the medium to long term.

A range of pests and diseases are observed in eucalypt plantations (Dell et al. 2008; Zhou and Wingfield 2011), but none currently appear to be having critical impacts on production in the areas we visited.

Landscape and soils

Land used for eucalypt forestry in Guangxi and Guangdong provinces includes reasonably flat units with deep soils, undulating hills and steep mountain slopes, some with very shallow surface soils. Elevations where eucalypts are grown range from close to sea level up to 2,000 m. Evidence of land degradation where topsoils have been eroded exposing the subsoil and parent rock, and sheet and gully erosion, are common features in the landscape. Soil groups include deep red soils rich in iron oxides, sometimes over limestone, lateritic soils over granite (Ultisols) and yellow-brown to yellow soils over sandstones (Dermosols).

Many soils are deeply weathered and parent materials include sandstone, siltstone, limestone and granite. Low availability of nutrients and soil compaction are commonly mentioned as growth-limiting factors. A common feature at sites on slopes in hilly terrain is shallow surface soils with low amounts of organic matter overlying uneven granitic parent material that is only 10–30 cm below the surface.

When soils are not stony, the columnar structure should enable root growth (Photo 25). Some growers' current practices of burning after harvests, or slash and litter removal for other uses, combined with the relatively small canopies developed by eucalypts in these landscapes are not conducive to the formation of a heavy litter layer. Thus, plantation soils in these regions do require careful management for sustainable production.

Typhoon damage is a serious threat to forestry in coastal areas of southern China. Plantations aged 1–2 years are very susceptible to damage, when trees may be broken close to the ground. Younger saplings blown over by typhoons are propped up with string while they recover. Older plantations are usually more resistant. One company plants 80% of its estate to typhoon-resistant clones (*E. urophylla* × *E. tereticornis*).

Photo 25. Deep soil profile over granite with low stone content and columnar block structure enabling good root penetration, Guangxi province

Landscape-level planting

In some regions, the entire landscape in steep terrain is planted with eucalypts, from the tops of the hills to the valley bottoms (Photo 27). The upper slopes of such terrain have shallow soils (Photo 26). They are highly vulnerable to erosion and degradation during various operations, for example slash removal and burning. In these landscapes there are no riparian vegetation buffers to protect watercourses or to retain biodiversity at the landscape level. Harvesting and replanting are conducted right to the bottom of the valley, which can affect stream flows and water quality.

Photo 28 shows a coppiced eucalypt plantation at age 4.5 years, at a site where weed control ceased after age 2 years. It has developed an understorey of shrub, grass and fern species and is supporting bird life. This is a productive site with a reasonably deep topsoil. This site and others like it show that it is possible to manage productive plantations while retaining some understorey diversity. However, Wen et al. (2005) recorded decline in the biodiversity of understorey species from the first to the second eucalypt plantation rotation at Dongmen Forest Farm in Guangxi province.

Photo 26. Shallow soil profile on sloping site with high proportion of large and small stones close to the soil surface, Guangxi province

Photo 27. Eucalypt plantations dominating a local landscape, Guangxi province

Site management

Burning to clear the previous vegetation before planting, especially on steep terrain, is still practised by some companies in Guangxi province. Slash and remaining vegetation are burned before the onset of heavy rains (see Photo 29).

Photo 28. Biodiverse understorey in a productive 4.5-year-old coppiced eucalypt plantation, Guangxi province

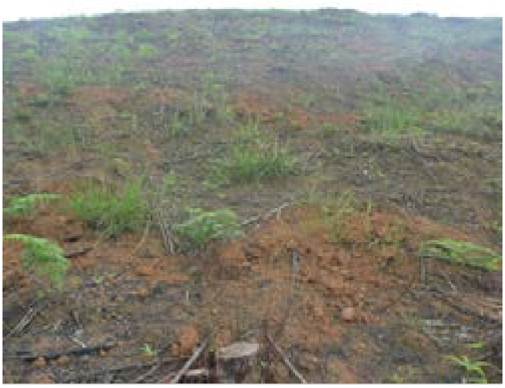

Photo 29. Exposed soil on a steep hillside after burning residues of the previous vegetation before establishing a eucalypt plantation, Guangxi province

Hot fires lead to near-complete loss of slash and litter (see Photo 29). This will undoubtedly lead to loss of much of the N in volatile emissions and loss of other nutrients as ash is blown away or washed downslope during subsequent rains. Soil erosion will accelerate in landscapes that have already suffered erosion losses. Burning is not an option prior to the coppice rotation, because fire would damage the tree stumps.

Slash, stumps and roots are collected by some growers for fuel in brick kilns and other local industries (Photo 30). This practice would degrade site quality (Section 3.2).

Some growers with plantations on gently sloping land control weeds by repeated deep cultivation with winged ploughs. Fertiliser is added in the furrows. As can be seen from Photo 31, this practice is not effective, as the dense weed cover along the tree rows is left to compete with the trees, while the tree roots growing in the inter-rows are cut or damaged by ploughing, reducing the ability of the young trees to access nutrients placed in the furrows. The consequences of this practice are discussed in Section 3.3.

Coppicing is a standard practice. It is generally managed by retaining one stem per stump; although, where survival of stumps is low, two stems may be retained.

Most growers apply high rates of fertiliser, typically a basal application in the planting hole followed by three or four follow-up applications, amounting to 2 kg of fertiliser salts per tree in the first rotation, and a further 1–1.5 kg per tree applied during the coppice rotation. Nutrition research trials were carried out at Dongmen Forest Farm and elsewhere during the late 1980s to develop fertiliser prescriptions (Simpson et al. 2003; Xu and Dell 2003). While the recommendations from these studies have been useful in the past, they may no longer be appropriate. Current trials appear to be aimed at testing the products of fertiliser companies, rather than improving the understanding of ecosystem processes to enable management of nutrient supply matched to tree demands through the rotation. Much has changed since the 1980s, including the rapidly expanding plantation land base, an increasing proportion of the plantation going through cycles of coppicing and replanting, reduced rotation lengths, and changes in weed control, site management practices and the genetics of planting stock. Meanwhile, the site and stand management practices have remained static, and are probably inefficient, without research-based refinement.

Research priorities

Sustainability of wood production from plantations is facing a number of risks, and there are corresponding opportunities to improve production and environmental outcomes. In the absence of reliable information from inventory on long-term trends in growth rates, expectation of increasing productivity and wood supply resulting from further breeding may be illusory. Key research issues are as follows:

Genetic improvement

The China Eucalypt Breeding Alliance provides a good model of pre-competitive collaboration among companies and between public and private organisations to improve the cost-effectiveness and impact of research.

Breeding and clonal selection should focus increasingly on reducing the risks to production from diseases, pests and climatic extremes such as typhoons, by developing material with improved resistance to these threats.

Site and stand management for improving productivity

Sound site and stand management is critical for long-term sustainable production, yet evidence of progress in this area over the last decade is lacking. It appears that research into site and stand management for improving and sustaining production is not receiving attention in either public or private organisations. This deficiency poses a significant risk to the ability of production from largely degraded landscapes to meet the rapid rise in wood demand. An integrated action agenda is required.

A collaborative applied research program along the lines of the China Eucalypt Breeding Alliance focusing on integrated system management may be an effective way to rejuvenate research in this critical area.

Some current practices such as burning slash and ploughing repeatedly are clearly damaging and need to be revised with the guidance of applied research.

Inventory databases, with further refinement in data collection, can and should be used to understand and explain the spatial and temporal variation in production. Such information would enable more targeted management practices to deal with the high variability in growth rates in the estate (Figure 21). In addition, systematically documenting relevant information including the germplasm planted and the stand management practices (site preparation, within rotation management, harvesting, etc.) for each rotation would help managers and researchers to interpret productivity trends over successive rotations.

Many soils on hilly and steep land discussed here are shallow and probably have low water-holding capacity. Soil-available water is a key variable determining productivity in seasonally dry environments such as those of southern China. Research into how attributes of terrain and soil processes influence production would enable development of more cost-efficient operational practices.

Photo 30. Harvest residues removed from the site and stockpiled for biofuel, Guangdong province. Photo: Stephen Midgley

Photo 31. Deep furrows ploughed in 1-year-old eucalypt plantation for weed control and fertiliser application, Guangdong province

It is important to understand the impact of spatial variation in water availability, as influenced by soil and topography, on productivity and its implications for deployment of genotypes, some of which will be better adapted to drought stresses experienced on shallower soils.

Current fertiliser practice seems to be based on little field experimental work.

Research is needed to establish the relative growth response to individual nutrient elements in the context of the changing genetic base and changes in soils.

Landscapes and biodiversity

The planting of entire landscapes with eucalypts does not allow for biodiversity maintenance at the landscape level and could have serious consequences for stream water quantity and biodiversity. The impact of eucalypt plantations on water resources is already an issue of public concern in China (Shi et al. 2012).

Plantation estates should be redesigned, wherever practical, to accommodate riparian vegetation development and biodiversity. By introducing belts of mixed native tree and shrub species along the boundaries of watercourses and on the steepest slopes, improved biodiversity and water outcomes may be obtained at the landscape level with little reduction in commercial wood production. This approach has been implemented by eucalypt-growing companies in Brazil.

4.5 Thailand

In Thailand, eucalypt plantations occupy about 500,000 hectares, and acacia plantations occupy probably less than 20,000 hectares. We visited eucalypt plantations in central Thailand, in areas encompassed by a 200 km radius east, west and north of Bangkok. In addition to block plantations, in many rural areas single or double rows of eucalypts along the boundaries of paddy fields are common in the landscape. Pulpwood is the main product. Three major pulp mills, located near Prachantakham in Chachoengsao province, Khon Kaen in north-eastern (NE) Thailand and Kanchanaburi in western Thailand, process eucalypt wood with a combined production of about 1 million tonnes of kraft pulp per year. Companies procure their wood from their own plantations, and from many small-scale farmers. They have a range of contract arrangements with farmers, and provide inputs such as planting material at reduced cost in exchange for a contract under which the grower sells them the wood at an agreed price. Such arrangements are described by Boulay and Tacconi (2012) and Boulay et al. (2012, 2013). Some woodchips are exported to other Asian countries.

Bark, slash and stumps from eucalypt plantations are now being sold as fuel for biomass-powered electricity-generation plants. The total removal of above- and below-ground biomass poses a serious threat to soil and to productivity of current and future crops (Section 3.2).

Breeding and deployment

Central and NE Thailand, where the majority of the eucalypt plantations are located, have seasonally dry tropical climates with mean annual rainfall in the range 1,100–1,800 mm. The length of the dry season (consecutive months in which mean monthly rainfall is less than 40 mm and evaporative demand is high) generally exceeds 4 months. Tropical provenances of *E. camaldulensis* are well adapted to this climate (Pinyopusarerk et al. 1996). In the late 1990s and early 2000s large quantities of seed collected from selected natural provenances of *E. camaldulensis* (Laura, Kennedy and Morehead rivers in far north Queensland) were imported to Thailand to meet the demand for seed during plantation expansion in NE Thailand. *Eucalyptus camaldulensis* and interspecific hybrids between it and other species including *E. deglupta*, *E. tereticornis* and *E. urophylla* are the dominant eucalypt taxa. Breeding of *E. camaldulensis* and *E. urophylla* by the Royal Forest Department commenced in the mid 1990s, and third-generation progeny trials of these are now under evaluation (Luangviriyasaeng et al. 2010).

Some hybrid clones have been developed opportunistically by selecting and testing natural hybrids arising from open-pollination in *E. camaldulensis* plantations. For example, the widely planted clone K7, a hybrid between *E. camaldulensis* and *E. deglupta*, was developed in this way. The companies have their own clonal selection programs, and some collaborate with the Royal Forest Department that has commenced controlled pollination to produce interspecific hybrids.

Breeding and deployment are now focused on creating interspecific hybrids, because pure-species *E. camaldulensis* is very vulnerable to eucalypt gall wasp. *Eucalyptus urophylla,* while more resistant to the wasp, is not suitable for planting along canal banks and rice field bunds because it is adapted to well-drained hill soils in its natural range in Indonesia and does not tolerate waterlogging.

Diseases and insect pests

Large areas of plantations, particularly in higher rainfall regions, have been defoliated by leaf blight diseases, notably *Kirramyces destructans* and *Cylindrocladium* sp. (Luangviriyasaeng 2003; Old et al. 2003; Dell et al. 2008). Failure of some vulnerable clones has led to a focus on finding pest- and disease-resistant clones. More recently, *E. camaldulensis* and some other clones have proved vulnerable to the eucalypt gall wasp *Leptocybe invasa* that emerged as a serious threat to wood production in the late 2000s.

Clones are deployed in monoclonal blocks, ranging in size from less than half a hectare to several hectares. In some landscapes, only one or two clones are planted. This creates serious problems when pests and diseases emerge, as is the case with clone K7 that has become vulnerable to the gall wasp. Despite its failure in the landscape (Photo 32), this clone is still being sold to growers.

While considerable areas of *E. camaldulensis* plantations that were established from best-provenance seedlots remain in production, most new plantations are now clonal.

Site and stand management

Most of the block plantations we visited were on flat to gently undulating terrain that in principle should help better management practices. Plantations are established using a range of practices including some forms of agroforestry involving intercropping. Cassava is sometimes grown between the trees rows in the first year after plantation establishment, which requires heavy ploughing and mounding (Photo 35). Rotations are short, typically 4–5 years from planting to the first harvest, followed by one or two successive coppice harvests at 4-year intervals.

Block plantations are typically established at spacings of 3 × 3 m, 3 × 2 m, and 3 × 1.5 m or 2 × 2 m. Following harvesting, new shoots from the coppice are thinned to two or three leading shoots per stump. Many growers aim for at least two successive coppice harvests before replanting; although, where clones have failed as a result of pest or disease attack, they are removed and the site is replanted with different genetic material.

Photo 32. Eucalypt clone K7 damaged by eucalypt gall wasp, *Leptocybe invasa*, resulting in low leaf area and curled and necrotic leaves

Photo 33. A 3-year-old monoclonal block of a eucalypt hybrid, resistant to gall wasp and leaf blight diseases, growing well in eastern Thailand

At planting, seedlings typically receive 200 g of 'NPK fertiliser mix', in some cases combined with animal manure or mill residues. Plantations are re-fertilised at a similar rate, early in each successive coppice rotation.

Weed control, which is essential for plantation growth, is almost exclusively by tractor ploughing along the inter-rows. This is a near-universal practice for all block plantations that we visited. The frequency of ploughing is two or three times per year adding up to some 8–15 ploughings per rotation. As seen in Photos 34 and 35, ploughing is not effective for weed control as a belt some 1 m wide along the tree rows remains infested with weeds. Repeated ploughing has degraded soil structure at many sites. Ploughing is driven by a desire to reduce weed competition and the risk of fire damaging or destroying plantations in the dry season.

Planting eucalypts along the bunds between irrigated rice fields, and in single or double rows along pathways, banks of irrigation canals, and roads in rice-growing farmlands, is a common practice. Trees in the rows are planted at close spacings, typically only 1 m apart, along the rows, but can achieve rapid growth because they have no competition from adjacent tree rows and can access the water in the adjacent paddy fields (Photo 36).

Research priorities

The potential for increasing wood production and hence profit from eucalypt plantations, with due environmental care, remains much under-realised in Thailand. The MAIs of 10–20 m^3 ha^{-1} y^{-1} being obtained by growers (Chapter 5) are less than what should be achievable under the prevailing climate and soil conditions in land that is generally flat and easy to manage. Furthermore, the overall system of management cannot be considered to be on a sustainable path.

Loss of R&D skills and absence of coherent research strategies

A major issue that may be retarding progress in Thailand is that planation forestry has remained isolated from the advances in integrated management developed in other countries over the past two decades. Thailand's public sector forest research agencies were strongly involved in international research on eucalypt and acacia plantation forestry in the 1980s and 1990s (primarily species and provenance testing,

Photo 34. Coppice rotation. Most trees have three coppice stems. Inter-rows have been ploughed twice or more each year since 2005. Note surface soil erosion down the gently sloping inter-row and absence of litter layer

Photo 35. Ploughed and mounded inter-rows in young eucalypt plantation. Cassava had been grown on the mounds. Note the weeds along the tree rows

and some research on stand and site management), but this collaboration had largely ended by 2000.

We saw little evidence of a R&D culture in public or private organisations. In the absence of applied research to support operational forestry, management practices appear to be static and bounded in past experience and beliefs. This can lead to further loss of R&D skills.

Genetic improvement and link with biological control of pests

Thailand has genetically broad-based and advanced breeding populations of *E. camaldulensis* and *E. urophylla*. Genetic resources of other tropical species that can hybridise with these two, including *E. brassiana*, *E. deglupta, E. pellita* and *E. tereticornis* are not as well developed. Breeders may need to develop complex eucalypt hybrids that combine traits of more than two species; for example, varieties developed for row-planting in rice-growing regions might need to combine the complementary traits of vigour (*E. urophylla*), tolerance of waterlogging (*E. camaldulensis* or *E. brassiana*) and pest and disease resistance (*E. pellita*). This will be a long-term undertaking but one that is already being pursued successfully in Brazil (Resende and Assis 2008). Effective biological control of the eucalypt gall wasp, as has been achieved in Israel, would assist Thailand.

Photo 36. A eucalypt trial on rice bund, central Thailand. The smaller trees in the left row are *E. urophylla*; those in the right row are *E. camaldulensis*

Deployment of clones

It is common for companies to identify one best clone and promote it exclusively. This is a very risky strategy and it would be better to promote 5–10 well-tested clones, aiming to progressively replace these with better ones at regular intervals as breeding and clonal testing continue (Section 3.1).

To reduce the risk of lost production or failure, individual monoclonal plantation blocks should be kept small (no more than 2 hectares) and dispersed across the landscape so that adjacent blocks comprise different clones. This may be hard to realise in landscapes in which many individual farmers decide what clones to plant, but it should be encouraged by the companies.

Companies should withdraw clones from sale once pest or disease problems that substantially reduce growth are evident. Since most clonal plantings are coppiced for two rotations, pest/disease-prone clones will remain in the landscape for 10–15 years even after sales of a susceptible clone cease.

Management for sustainable production

We saw no experimental work undertaken by either public research organisations or companies to improve the management of plantations. Some plantation managers seemed to lack insight into the principles of soil, site and stand management. They were largely unaware of the potential adverse effects of repeated inter-row ploughing two to three times per year, and its ineffectiveness for weed control. We saw sites in the third coppice rotation that would have been ploughed more than 25 times. There has been little adoption of herbicide technology. Ploughing is seen as the only way to control weeds.

There is a need to foster thinking that links soils, nutrient cycling, nutrient management and vegetation management as interrelated aspects. For example, rate and timing of fertiliser application is often not based on an understanding of the nutritional demand by trees through the rotation, and fertiliser applied along the tree rows that have vigorous weed growth will be largely wasted or will promote more weed growth.

Although postharvest removal of total aboveground biomass and stumps for bioenergy is commencing in some regions, no attempt has been made to quantitatively evaluate the effects of such practices in depleting the site resources affecting production.

Experimental research into plantation management integrating the variables determining productivity is much needed. Of particular importance may be a local review and reassessment of potentially damaging practices including total biomass harvest and repeated ploughing.

There is a need to improve fire management, through approaches including collaboration with local communities to reduce fire frequency, strategic establishment of firebreaks adjacent to roads and tracks, and improved fire suppression capability.

Inventory for understanding productivity in space and time

Wood production data are mostly collected at harvest as the total weight of wood on truck at the compartment level. This does not allow examination of productivity at the site level, or comparison of production in successive rotations. Without such examination, it is not possible to understand spatial and temporal variability in production, which is necessary to manage the estate sustainably and to invest in practices for improving production.

Company R&D should be linked to systematic inventory based on permanent sample plots or cruising preharvest inventory, backed by sound recording of site history.

Tree plantings in rice fields

Row plantings along paddy field boundaries, canals and roads in rice-growing areas provide more than half of the eucalypt wood yield in some districts. These plantings appear the most promising current development in Thai eucalypt forestry. The methods for sustainable system management are very different to those for block plantings. One experimental study at two locations in Chachoengsao province (Luangviriyasaeng 2008) showed that growing eucalypts had no negative impacts on rice production up to age 4 years after planting.

Follow-up studies would be valuable over a wider range of conditions to confirm the finding that rice and wood production can be integrated without reduction in rice yields.

The need for a coherent R&D strategy

To help eucalypt plantation forestry become more sustainable and productive, we recommend a program of collaborative research on sustainable management funded by a cooperative of major companies, working in collaboration with the Royal Forest Department and other institutions such as universities. As a precursor, key stakeholders and representatives of smallholder growers could develop a coherent R&D priority strategy.

5 Productivity: trends and variations

We analysed and reviewed the spatial and temporal trends and patterns in wood production achieved in commercial forestry operations, using data supplied by collaborating organisations. Data for Indonesia, Sabah (Malaysia), China, Thailand and Vietnam were from private companies, except for a small part of the data from Vietnam that came from government research and production centres. This large database allowed us to examine ecosystem-level production with multiple sample points in space and time. Planting dates of the stands that contributed to the data were in the range 1990–2010.

We visited all growers who contributed data, presented the scope and goals of the project, explained the conditions for using and reporting their information, and discussed their plantation inventory systems. We visited plantations with operations and research managers to discuss and understand previous and current management practices.The regional basis and nature of collaborators involved in the study are shown in Table 13. These collaborators manage about 20% of the plantation areas in the regions, except in Vietnam, where plantation ownership is highly dispersed, and the collaborators manage about 10,000 hectares of acacia plantations.

The number of collaborators is not directly related to the amounts of data received. Some provided substantially more data than others.

The objectives of the analysis were to:

- examine the trend, range and variation in plantation productivity from commercial plantations
- analyse the patterns of distribution in productivity classes based on mean annual increment (MAI) across the estates
- examine the trend in growth rates across two or more rotations where possible
- identify parameters that may have had major impacts on production.

Not all these objectives could be met at all locations because of constraints on the availability of appropriate data.

5.1 Methods and database

From each grower, we requested a subset of inventory data representative of the estate, rather than information covering the entire estate. All collaborators consider their inventory data commercially sensitive, and they provided data on the understanding that the identities of individual company/grower estates would not be revealed in the report. We have complied with that principle; thus, within each major ecological region such as Sumatra, Sabah, and Vietnam, data are identified as representing subregions 1, 2, 3, etc. These subregions are in most cases geographically separate, but in some cases different

Table 13. Plantations and regions covered in the study

Genus	Region	Latitudinal range	Countries	Growers collaborating
Acacia	Sub-equatorial seasonally dry tropics	10°S–22°N	Vietnam	6
Acacia	Equatorial humid tropics	6°S–6°N	Indonesia (Sumatra)	2
Acacia	Equatorial humid tropics	4°N–6°N	Malaysia (Sabah)	2
Eucalyptus	Equatorial humid tropics	6°S–6°N	Indonesia (Sumatra)	1
Eucalyptus	Sub-equatorial seasonally dry tropics	13°–15°N	Thailand	4
Eucalyptus	Seasonally dry tropics/subtropics	21°–23°N	China (Guangdong and Guangxi provinces)	7

subregions overlap geographically. Each subregion was managed by a single grower organisation; however some grower organisations managed more than one subregion.

The following information, relevant to interpretation of productivity data, was collected during our visits and subsequent correspondence:

- genetic base of planting stock
- age of stands at inventory or harvest
- stocking at inventory or harvest
- management practices including site preparation, initial stocking, vegetation management, and fertiliser application, and how these changed over successive rotations
- incidence of pests and diseases, and the damage caused by them.

Where possible, soils were examined in the field. Most growers had little or no information linking inventory with soils, except in a general way. Variation in climate, particularly rainfall, affects productivity, but an evaluation of this was not within the scope of this study.

In Sumatra and Sabah, inventories were available for two rotations of acacia but no individual permanent sample plots or compartments were inventoried over both rotations. Direct comparison of growth rates over two rotations for the same compartments was only possible using limited datasets from Vietnam. Data on eucalypts from China were primarily from the first rotation, with some information from coppice stands. From Thailand, only very limited data were available. In general, large companies had reasonably well-developed inventory systems.

Inventory

Inventory data were collected using three different approaches, hence they vary in their detail:

1. *Preharvest inventory (PHI) from randomly located inventory plots*: These were from sample plots (typically 0.05 ha), located in many blocks (management units) representing a subregion. Some growers in China and Sumatra provided this type of data, collected as preharvest inventory. Details on the average age of stands and the number of plots are presented in relevant tables.
2. *Cruising inventory at block level:* These were volume estimates for blocks, typically 1–10 ha in area. They were estimated by inventory of plots or rows that represent 3–5% of the block area. This was usually carried out just before harvest. Such data were provided by some acacia growers in Vietnam and Sabah and some eucalypt growers in China.
3. *Wood weighed on trucks at the weighbridge*: Total green weight of truckloads of wood from each block. This type of data was provided by some growers in Sabah and Thailand.

Each of these approaches involves several approximations. For methods 1 and 2, height and diameter at breast height of all trees in plots were measured, or in some cases height was measured only on a proportion of the trees. From these data, individual tree volumes were calculated using a stem-form factor or volume equation developed locally for the species involved. Differences in stem form caused by genotypes, stocking and soil fertility are likely but are not accounted for here. In most cases, volume over bark to 4 cm small-end diameter was calculated, although this diameter varied by 1–2 cm with changes in harvesting practices. Individual tree volumes were summed to obtain total volume for the plot and, for method 2, for the block. Rotation length was calculated from the time from planting to inventory (specified to the nearest month). MAI was estimated at the level of the plot (method 1) or block (method 2). In each case we used volume estimates provided by collaborators, checking the methods as much as practical. Method 3 assumes accurate matching of truckloads to specific compartments. Conversion from green weight to volume over bark uses green densities that are approximations and assumes retention of all bark on the logs, whereas in practice some bark may be lost.

Volume estimates of the different collaborators did not follow a standardised inventory protocol (although within each company, methods were consistent over time). Not all of the subsets of the inventory data given to us were drawn by unbiased statistical sampling techniques. Major contributors to the data provided valid responses to subsequent questions on errors, representativeness, potential bias and numerous other points, strengthening confidence in the analysis.

Age of inventory influences MAI estimates. Plots or blocks less than 3 years old at inventory were excluded from the data. If inventory is conducted before half rotation age, MAI will be somewhat higher than that for the full rotation. For most datasets, inventory was taken at ages beyond half the corresponding rotation length. Volume curves from experimental work with a hybrid eucalypt clone at a site in southern Guangxi Province, China (Chen et al. 2011), showed that MAIs remained quite stable from year 3 to year 7. In experimental trials of *A. mangium* in South Sumatra, MAI remained stable from year 3 to year 7, varying by less than 12% during this period and then declined in year 7 (Hardiyanto and Nambiar 2014). Similarly, in a trial of *A. auriculiformis* in southern Vietnam, MAI was stable from year 3 to year 6 inclusive, varying by less than 10% over this period (Huong and Nambiar, unpublished data). Another source of bias would be the tree death between the inventory and final harvest, if the time between them is substantial. For these reasons, stockings are reported in all cases. Despite these unavoidable limitations, we believe that, overall, the data provide a realistic assessment of productivity in commercial plantations.

5.2 Results

Acacia mangium and *Eucalyptus pellita*: equatorial humid tropics (Sumatra, Indonesia)

The range and the large variation in growth rates in successive planting years spanning a 15-year period, for two rotations within subregions 1 to 3 in Sumatra, are shown in Table 14a and Figure 12. The plantings in the later years (1993–94) of the first rotation yielded lower than in the earlier years. The reasons for this are not known but could be due to soil differences in the planted areas (see Photos 1–4) and other land attributes. The rates of growth in the second rotation were, in general, as good as or marginally better than the first. This was likely to have been brought about by the deployment of genetically improved planting stock (E.B. Hardiyanto pers. comm.) and improved management including organic matter conservation and weed control (Hardiyanto and Nambiar 2014). MAIs for planting years in Figure 12 ranged from 22–33 m^3 ha^{-1} y^{-1} in the first rotation and from 26–35 m^3 ha^{-1} y^{-1} in the second rotation. The mean age to inventory and harvesting decreased by about 2 years from first to second rotation (Figure 13) without reductions in MAI. A notable feature of the data is the high variation in MAI within the area planted in any one year, and the persistence of that variation in the second rotation (standard deviations for each year are shown in Figure 12). The frequency distribution of yield classes (defined by MAI) for subregions 1–3 combined (Figure 14) shows the high variation in MAI across the estate. However, it is notable that in the second rotation, 54% of plots grew at MAI between 30–40 m^3 ha^{-1} y^{-1} and 16% of plots had MAIs exceeding 40 m^3 ha^{-1} y^{-1}. The proportion of plots with MAI below 25 m^3 ha^{-1} y^{-1} was reduced in the second rotation. The reductions in mean stocking at time of inventory from the first to the second rotation by 230 and 150 stems ha^{-1} respectively in subregions 1 and 3 are attributable in part to the implementation of singling to produce a single stem in the second rotation.

Growth rates of plantations in subregions 4–6 of Sumatra (Table 14b) were similarly high for the first rotation of *A. mangium*, with mean MAI ranging from 27–34 m^3 ha^{-1} y^{-1}. However, in two of the subregions, growth rates in the second rotation dropped markedly, to 15 and 17 m^3 ha^{-1} y^{-1}. This is primarily due to the mortality caused by *Ganoderma* root rot and stem canker diseases. There is a much higher proportion (36%) of inventory plots with productivity below 15 m^3 ha^{-1} y^{-1} in the second rotation as compared with the first (15%) (Figure 15). The rapid spread of *Ceratocystis* stem wilt/canker, commencing in 2010, has also caused high mortality in Sumatra, although it only became evident in subregions 1–3 in the third rotation.

Recognising the challenge for wood production posed by diseases, growers have been progressively replacing *A. mangium* with *E. pellita,* some ahead of others. All the plantations of *E. pellita* are located on sites that were under one or two rotations of *A. mangium*. Current growth rates of *E. pellita* are lower than for *A. mangium*, ranging from 15–18 m^3 ha^{-1} y^{-1} across subregions 4–6. Of particular note is the very high variability in growth within each region, with the coefficient of variation of MAI inventory plots ranging from 54–72%, much higher than for the first rotation of *A. mangium*. The frequency distribution of productivity classes of *E. pellita* is different from that of *A. mangium* (Figure 16), with 30% of plots having MAI below 10 m^3 ha^{-1} y^{-1}. The linear regression between stocking at inventory and MAI (Figure 17) showed that variation in stocking accounted for 47% of the variance in MAI for *E. pellita,* illustrating the critical importance of maintaining high stocking to achieve productivity.

Table 14a. Summary of plantation productivity in Sumatra, Indonesia: subregions 1–3: *Acacia mangium*

	Rotation	No. of plots	Mean age (years)	Mean stocking (stems ha^{-1})	MAI (m^3 ha^{-1} y^{-1})		
					Mean	s.d.	c.v. (%)
Subregion 1	1	98	7.5	1061	32.5	7.3	22
	2	35	5.9	834	33.9	6.8	20
Subregion 2	1	69	8.3	828	22.4	6.0	27
	2	24	5.6	863	35.0	10.2	29
Subregion 3	1	176	8.1	1194	35.2	5.1	14
	2	52	5.9	1043	34.0	6.5	19

Table 14b. Summary of plantation productivity in Sumatra, Indonesia: subregions 4–6: *Acacia mangium* and *Eucalyptus pellita* (plots in age range 3 to 7 years)

	Species	Rotation	No. of plots	Mean age (years)	Mean stocking (stems ha^{-1})	MAI (m^3 ha^{-1} y^{-1})		
						Mean	s.d.	c.v. (%)
Subregion 4	AM	1	1270	3.6	1092	27.3	10.9	40
	AM	2	1132	4.5	1158	28.6	10.4	36
	AM	3	60	4.9	643	11.2	4.7	42
	EP	1/2	1766	4.2	937	15.6	8.9	57
Subregion 5	AM	1	36	6.7	641	27.1	7.7	28
	AM	2	747	5.0	723	14.5	10.5	72
	EP	1/1	1156	4.3	868	17.6	9.5	54
Subregion 6	AM	1	153	5.7	838	33.6	11.7	35
	AM	2	481	4.5	708	16.6	11.6	70
	EP	1/1	852	4.3	758	16.7	12.0	72

Note: AM= *A. mangium*, EP = *E. pellita;* for *E. pellita,* rotation 1/1 indicates the first rotation of this species after one rotation of *A. mangium*, rotation 1/2 the first rotation of *E. pellita* after two rotations of *A. mangium.*

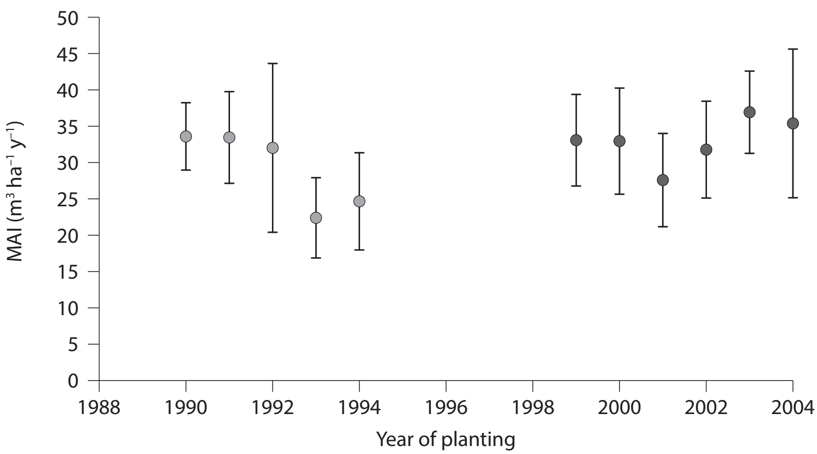

Figure 12. MAI by planting year, for first-rotation (light grey) and second-rotation (dark grey) *Acacia mangium* plantations, subregions 1–3, Sumatra (data from subregions combined, vertical bars show standard deviation)

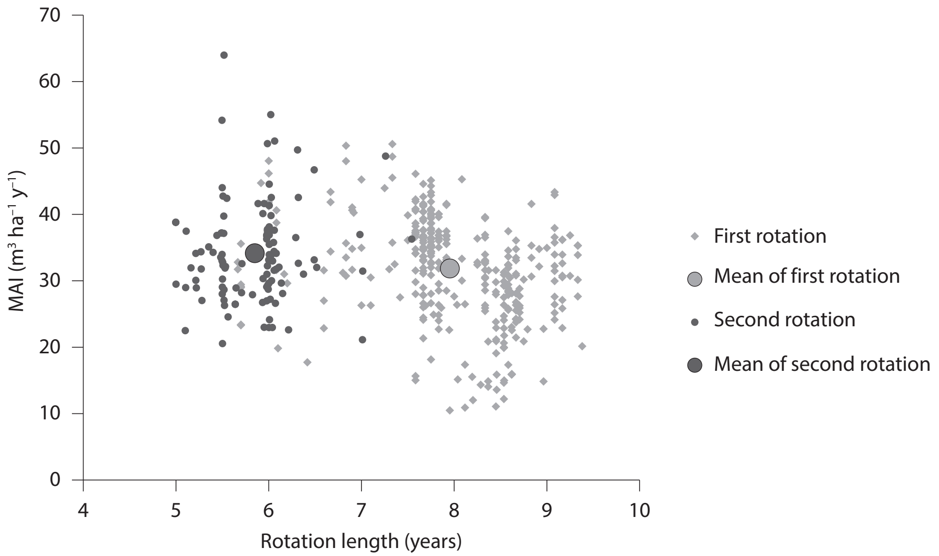

Figure 13. MAI of individual inventory plots for first- and second-rotation *Acacia mangium* plantations, showing rotation length, subregions 1–3, Sumatra (data from subregions combined)

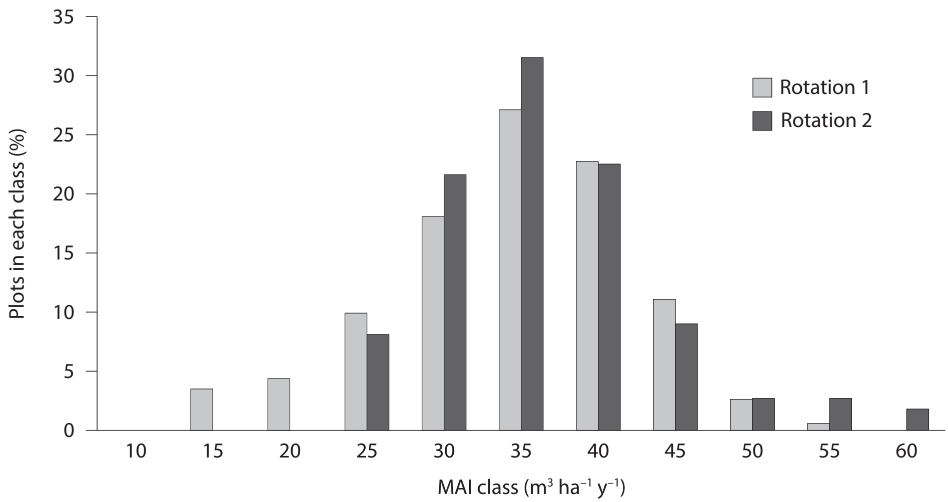

Figure 14. Proportions of inventory plots in different MAI classes for first and second rotations of *Acacia mangium*, subregions 1–3, Sumatra (the numbers under the x-axis are the upper bounds of each MAI class; data from subregions combined)

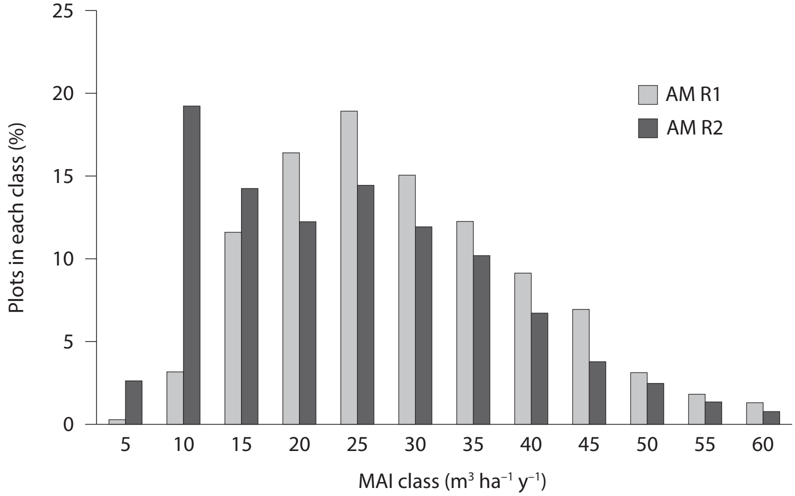

Figure 15. Proportions of inventory plots in different MAI classes for first and second rotations of *Acacia mangium*, subregions 4–6, Sumatra (the numbers under the x-axis are the upper bounds of each MAI class; data from subregions combined)

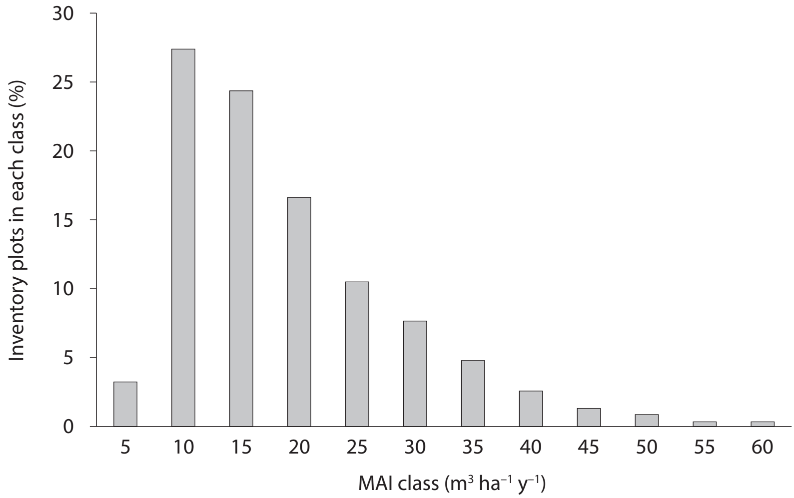

Figure 16. Proportions of inventory plots in different MAI classes for *Eucalyptus pellita*, subregions 4–6, Sumatra (data from three subregions combined; the numbers under the x-axis are the upper bounds of each MAI class)

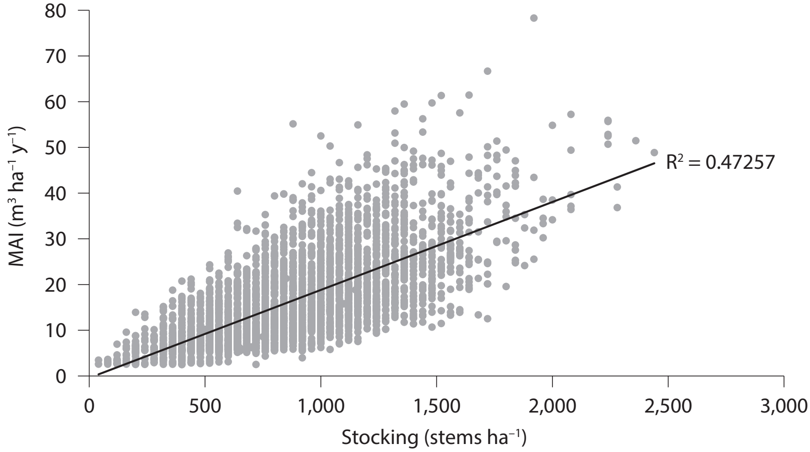

Figure 17. Relationship between stocking at inventory and MAI for inventory plots of *Eucalyptus pellita*, subregions 4–6, Sumatra (data from three subregions combined)

Acacia mangium: equatorial humid tropics (Sabah, Malaysia)

Data from permanent sample plots (0.05 hectares in area) were available from first- and second-rotation plantations in subregion 1. At age 8 years, mean MAI of the first-rotation plots was 24.1 m^3 ha^{-1} y^{-1} (n = 22, s.d. = 8.6), while that of second-rotation plots was 26.7 m^3 ha^{-1} y^{-1} (n = 12, s.d. = 7.0). Sample numbers are too small to draw conclusions about estate-wide production. The importance of maintaining stocking is clear (Figure 18). The regressions between stocking at age 8 years and volume were identical for both first- and second-rotation stands, accounting for 52% of the variance in the combined set of first- and second-rotation plots, as shown in Figure 18. Weighbridge data from a total of 239 harvested blocks from the same subregion, with rotation ages ranging from 7–15 years, are shown in Figure 19. The progressive decline in MAI as rotation age increases is evident. Second-rotation productivities were slightly higher than those from the first-rotation, for those rotation ages where comparisons could be made.

A company in subregion 2 has been improving management practices since 2008. This has improved growth rates (Table 15). Although only inventory at age 2.5–4 years is available, there is an upward trend in early growth for plantations established in 2009 and 2010. This improvement may be associated with improved seeds and weed control, the latter by a change from manual to herbicide application. Cable logging has replaced tractor logging on steeper slopes, to reduce soil damage. However, stocking and hence productivity are likely to decline in the new *A. mangium* plantings, because of the impact of *Ceratocystis* stem wilt/canker that has been severe.

Acacia: seasonally dry sub-equatorial tropics (Vietnam)

Data were from preharvest inventories of blocks ranging in size from 1–33 ha. All sites in Table 16 had one or more previous rotations of acacia. Growth rates were slower at sites in the north where cool, cloudy winters prevail. Acacia hybrid in the north had an average MAI of 17.6 m^3 ha^{-1} y^{-1}, higher than *A. mangium* with 11.4 m^3 ha^{-1} y^{-1}, although only four *A. mangium* blocks were sampled. Few inventory data were available from central Vietnam; however a recent study by (Dong et al. 2014) reported high growth rates for acacia hybrid plantations in the lowlands of Hua Thien Hue province. The mean standing volume for six 225 m^2 plots in 5-year-old plantations was estimated to be 139.3 ± 34.5 (s.d.) m^3 ha^{-1}, equivalent to an MAI of 28.7 m^3 ha^{-1} y^{-1}.

Growth rates of acacia hybrid in the south averaged 23 m^3 ha^{-1} y^{-1}. For these blocks, the data from the previous (first) rotation were available. A comparison of MAIs for the two rotations is shown in Figure 20. Productivity of each block is indicated by a single point on the graph. The MAIs of 15 of 21 blocks are above the 1:1 parity line on the graph, indicating that growth rates were higher in the second rotation than the first. Several factors would have contributed to this change, especially the improvements in genetic stock and management. Company 1 grew *A. auriculiformis* in the first rotation, then changed to acacia hybrid. Company 2 grew *A. mangium* in the first rotation and changed to acacia hybrid. Stocking did not change between rotations for these two companies. Company 3 grew acacia hybrid in both rotations but increased the initial stocking

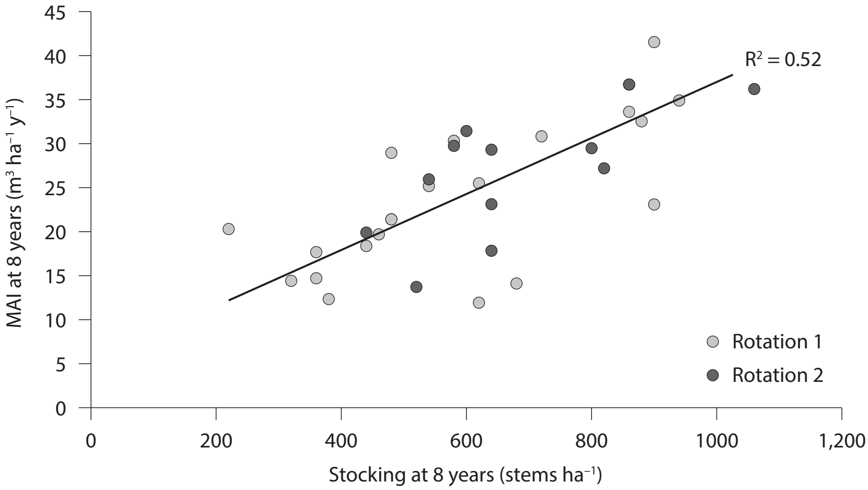

Figure 18. Relationship between stocking at inventory and MAI for first- and second-rotation inventory plots of *Acacia mangium*, subregion 1, Sabah

Table 15. Characteristics of plantation blocks planted in successive years in subregion 2, Sabah (changes in seed sources, harvesting and vegetation management practices commenced in planting year 2008)

Planting year	No. of blocks	Mean age (y)	Mean stocking (stems ha^{-1})	MAI (m^3 ha^{-1} y^{-1})		
				Mean	s.d.	c.v. (%)
2007	100	5.1	402	10.1	5.4	52.9
2008	54	3.4	689	15.6	5.8	37.0
2009	61	3	661	18.5	7.8	42.1
2010	61	2.5	1003	29.5	6.1	20.6

Table 16. Mean and range of second-rotation MAI for production blocks of different acacia species in Vietnam

Region		No. of blocks/ treatments	Mean age (y)	MAI (m^3 ha^{-1} y^{-1})			
				Mean	Range	s.d.	c.v. (%)
Northern Vietnam	*A. mangium*	4	5.8	11.4	8.0–15.8	3.3	19
	Acacia hybrid	10	6.6	17.6	14.3–22.5	3.2	16
Central Vietnam	*A. mangium*	2	7.5	11.2	11.0–11.4	–	–
	Acacia hybrid	1	7.0	11.8	–	–	–
Southern Vietnam	Acacia hybrid	19	6.4	23.0	16.5–28.6	3.7	16

from 1,111 trees ha–1 in the first rotation to 1,666 trees ha–1 in the second. Management practices such as weeding and fertiliser application also would have changed over time. Overall, Figure 20 shows that productivity either remained the same or increased from the first to the second rotation, demonstrating the opportunities for increasing production.

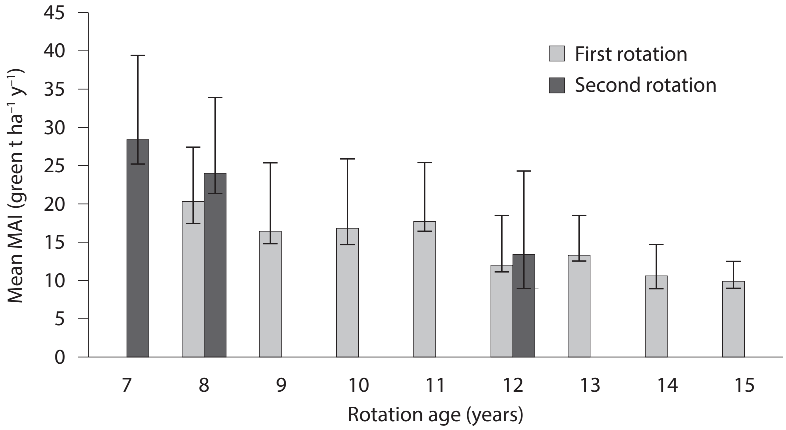

Figure 19. Productivity of first- and second-rotation *Acacia mangium* blocks, determined from green wood weights delivered to the mill, for different rotation ages, subregion 1, Sabah. (Lengths of error bars above each column show standard deviations, and downward error bar standard errors; each age-by-rotation class shown by a column represents six or more plantation blocks.)

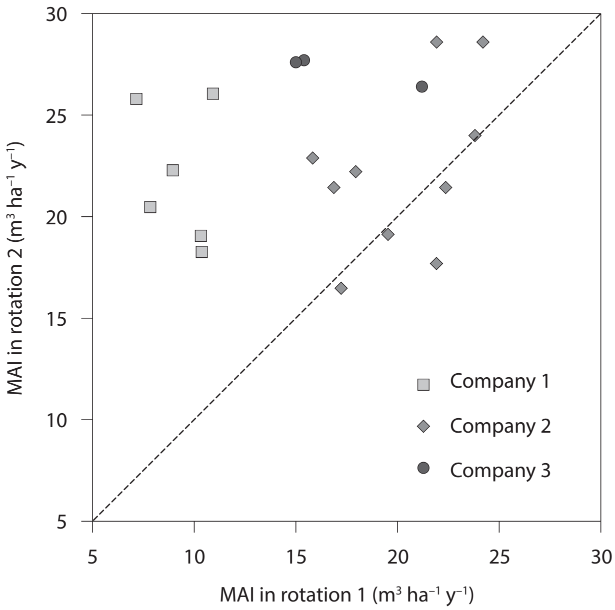

Figure 20. Productivity of two successive rotations in acacia plantation blocks of three companies in southern Vietnam

Eucalyptus: seasonally dry tropics/subtropics (Guangdong and Guangxi provinces, southern China)

Data for the first rotation representing nine subregions and three grower organisations in two provinces are presented in Table 17. Overall, mean MAIs of subregions are in the range 17–28 m^3 ha^{-1} y^{-1}. Many of these sites had carried previous rotations of eucalypts or other tree species managed by other organisations, but records of earlier management were not available for this study. All data presented relate to stands planted since 1995. In all but one subregion, data from coppiced blocks were insufficient to compare their productivity with planted blocks. The growth rates from subregions 1–4 are considered representative of the estate because inventory plots were located randomly across all the areas within compartments including on unplantable (e.g. rocky or swampy) sites. This is reflected in the high coefficients of variation (47–56%) for plot MAIs for these regions. These four subregions encompass many small plantation units, and are separated by 50–100 km.

Distributions of MAI classes in two of the first four subregions are shown in Figure 21. Both subregions have similar proportions of plots in each productivity class. We were informed that more than 60% of the total area represented in Figure 21 was planted with a single clone. The high variation in growth rates across the land is likely to be mostly due to differences in soil, environment and management.

For subregions 5–9, some blocks that were damaged or destroyed, with non-commercial wood volumes (equivalent to MAI < 10 m^3 ha^{-1} y^{-1}), were excluded from the data. Subregion 9 had blocks classified into two site classes, B (more productive) and C (less productive), on the basis primarily of soil depth, soil type and rainfall. While most data from this subregion came from planted blocks, 79 coppiced blocks were included. However, inventories from the previously planted harvests from these blocks were not available, so growth is not strictly comparable. MAIs for planted blocks of Site class B were slightly higher than for planted Site class C (17.4, compared with 16.3 m^3 ha^{-1} y^{-1}), while the mean MAI of coppiced blocks of Site class B was somewhat higher at 22.3 m^3 ha^{-1} y^{-1}. The linear regression of MAI on stocking for planted blocks of Site class B showed that variation in stocking accounted for 33% of the variance in MAI (Figure 22). This result suggests that in order to sustain productivity the initial plantation stocking (decided by local managers) should be maintained as far as possible throughout the rotation by managing to minimise mortality.

Table 17. First-rotation eucalypt plantation productivity for three groups of subregions in Guangdong and Guangxi provinces, China

Subregion/ site class	No. of plots/ blocks	Mean stocking (stems ha^{-1})	Mean age (y)	MAI (m^3 ha^{-1} y^{-1})		
				Mean	s. d.	c.v.
Subregion 1	201	1189	4.0	19.7	9.3	47
Subregion 2	354	1444	3.9	18.8	9.5	50
Subregion 3	71	1534	3.8	16.3	9.3	57
Subregion 4	363	1221	3.9	17.4	9.8	56
Subregion 5	30 (blocks)	1612	5.9	28.3	8.6	30
Subregion 6	32 (blocks)	1215	5.3	27.5	4.1	15
Subregion 7	12 (blocks)	1180	5.4	25.2	5.6	22
Subregion 8	25 (blocks)	1155	5.9	23.8	3.7	16
Subregion 9 Site class B (planted)	429 (blocks)	1035	6.8	17.4	5.0	29
Site class B (coppiced)	79 (blocks)	1135	5.6	22.3	8.2	37
Site class C (planted)	39 (blocks)	926	6.7	16.3	8.5	34

Note: For subregion 9, blocks with age greater than 8 years were excluded.

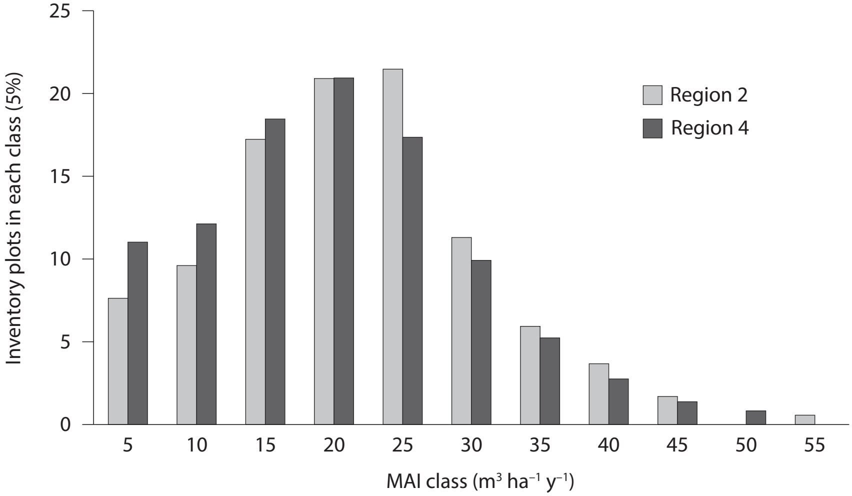

Figure 21. Proportions of inventory plots in different MAI classes for first-rotation eucalypt plantations in two planting subregions in China (the numbers under the x-axis are the upper bounds of each MAI class). Note: The numbers under the x-axis are the upper bounds of each mean annual increment (MAI) class

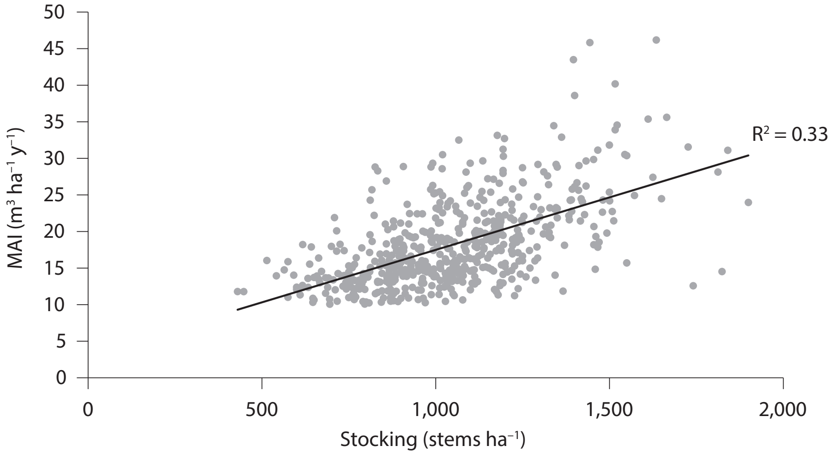

Figure 22. Relationship between stocking at inventory and MAI of planted eucalypt blocks of Site class B, Subregion 9

Eucalyptus: seasonally dry sub-equatorial tropics (Thailand)

Data from Thailand were very limited and confined to central Thailand. Green weight from blocks (Table 18) shows that growth rates are in the range 15–20 green tonnes ha^{-1} y^{-1}. The MAI in m^3 ha^{-1} y^{-1} would probably be 5% higher, because the green wood density is about 1,050 kg m^{-3}. Yields from blocks that were coppiced or replanted following the first planted stands ranged from 9–26 t ha^{-1} yr^{-1}. After coppicing, two or three stems per stump were retained. Stocking (stems per hectare) was therefore much higher in the coppiced stands relative to the previous planted ones.

Table 18. Wood production from one, or two successive, eucalypt harvests from plantation blocks in Thailand

Subregion	First harvest after planting			Second harvest (coppice or replant)			
	Length of rotation (y)	No. of blocks	Productivity (green tonnes ha^{-1} y^{-1}, mean and range)	Replant or coppice	Length of rotation (y)	No. of blocks	Productivity (green tonnes ha^{-1} y^{-1}, mean and range)
1	4	8	19 (7–23)		–		–
2	4.2	2	31 (27–34)		–		–
3	3–5	3	23 (18–28)	replant	3–8	3	22 (16–26)
4	5–6	3	12 (10–13)	coppice	5–6	3	10 (9–11)
5	4.9	1	15	coppice	4.0	1	19

5.3 Discussion

Although short-rotation plantations have been grown for three or more decades in SE Asia, efficient systems for monitoring productivity (including Permanent Sample Plots and systematic preharvest inventory) and recording associated site data, and effective data capture and retrieval, are still evolving. Some companies now have well-developed systems (e.g. *A. mangium* and *E. pellita* in Sumatra—Table 14, Figures 12–17; and eucalypts in China—Table 17, Figures 21–22), so there will be a better regional database for studying sustainable production in the future. In some subregions the assessment of productivity relies on estimates made on standing crops by wood merchants or records of green weights of harvested wood from compartments. Reliable and fair systems of measurement of volume or weight of harvested wood are needed to enable thousands of small growers in some countries to receive due returns from the wood that they grow.

Data available for two rotations of *A. mangium* in Sumatra and to a lesser extent in Sabah show that productivity has remained very similar for the first and second rotation, and improvements in plantations established in later years were modest at best (Table 14, Figures 12–15 and 19). This is surprising given the introduction of genetically improved planting material in the second rotation (Figure 2). In some subregions of Sumatra, negative impacts of diseases on productivity were substantial. This points to the need for caution in extrapolating genetic gain derived from experimental results to operations, thus raising unrealistic expectations from breeding. However, long-term experimental studies in South Sumatra show the high growth potential of *A. mangium* in successive rotations reaching MAI of 43–48 m^3 ha^{-1} y^{-1} (Table 12, Hardiyanto and Nambiar 2014), as also seen in some inventory plots (Figures 14 and 15). In recent years, growth rates of *A. mangium* have clearly suffered from diseases in many regions. In subregions 4–6 of Sumatra, a much higher proportion of second-rotation inventory plots had MAI below 15 m^3 ha^{-1} y^{-1} compared with the first rotation (Figure 15). In contrast, assuming that impacts of diseases remain low, opportunities exist for increasing productivity of acacias in Vietnam. Levels of productivity measured in well-documented experimental studies in southern and central Vietnam are substantially higher than averages achieved in nearby operational plantations (Figures 11, 20). There, the main current challenges are posed by poor site management (Section 4.4) and failure to apply integrated management practices.

The high variation in MAI within the area planted in any single year across the land base, and the persistence of that variation in the second rotation (Figures 12–15) is a striking feature of the analysis, despite the views of managers that management had improved over time. This variation is reflected in the coefficients of variation for MAIs within subregions that were as high as 40% in the first rotation, and even higher in the second rotation in some subregions, because of disease. In Sumatra, the average growth rate of *E. pellita* is significantly lower than that of *A. mangium* grown previously in the same areas, and is also highly variable (Figure 16). Clearly, the change from one species to another is not without challenges. However, *E. pellita* has the potential for fast growth: 17% of plots had MAI greater than 25 m^3 ha^{-1} y^{-1}. Information from the company indicates that a major reason for the poor growth was that a widely planted clone was highly sensitive to attack by *Botryosphaeria* stem canker. This clone is no longer planted.

No data are available on the productivity of eucalypts from the same sites over successive rotations. A review of eucalypt forestry in China (Turnbull 2007) reported MAI as increasing from an average of 7 m^3 ha^{-1} y^{-1} for plantations established before 1991 to 20 m^3 ha^{-1} y^{-1} in post-2001 plantings, this increase being associated with changes in species planted and management practices. However, Xu et al. (2008) report low MAIs of 6–7 m^3 ha^{-1} y^{-1} in an experiment comparing a range of slash and litter management treatments in a second-rotation plantation of *E. urophylla* established in 1997 in Guangdong province. We found no inventory records tracking productivity changes over successive rotations in any of the plantation estates that we studied. Current MAI for well-sampled subregions in China ranged from 16–23 m^3 ha^{-1} y^{-1}. The small amount of data from Thailand suggests that productivities are somewhat lower there. In the absence of experimental work conducted in the regions, examining the potential productivity (as is available for acacias, Table 12, Figure 11), it is not possible to benchmark the current productivity and scope for improvement of eucalypt plantations. In Chapters 2 and 3, we reviewed several potentially site-degrading management practices currently applied in eucalypt plantations. Unless these are replaced with practices that conserve site capacity, expectations of increases in productivity are unlikely to be realised.

Equally important is the evidence of high variation in eucalypt plantation productivity within and across the management units (Figure 21–22). Such variation occurs even in areas planted primarily with a single clone, illustrating the importance of integrated management to achieve uniform, high productivity: the use of clones alone does not suffice. When comparing coefficients of variation in different subregions in China it should be noted that the high standard deviations of 47–57% for subregions 1–4 are for 0.05 ha plots, while the somewhat lower standard deviations for subregions 5–9 are for larger plantation blocks (subcompartments).

Our discussions with data providers showed that for most, but not all, growers there is little quantitative information on factors determining productivity in space and time within their respective land bases. It was beyond the scope of this project to evaluate the contributions of various site and stand factors (e.g. slope, aspect, elevation, soil depth, soil characteristics, methods of harvesting and site preparation, vegetation management and planting stock) to the levels of productivity achieved in operational plantings. Relevant biophysical principles, risks, opportunities and experimental evidence were reviewed in Chapter 3. However, one relationship commonly identified here and applicable to all species is that between stocking at preharvest inventory and total volume. As an example, the linear regressions of stocking accounted for 30–50% of variance in MAI in most subregions (Figures 17–18, 22, other data not shown). Clearly, research on and management of survival throughout the rotations is a priority.

In summary, *A. mangium* in Indonesia and Malaysia has been highly productive, but with high spatial variability, for two rotations, but its long-term future is under threat from diseases. In Vietnam, where diseases and pests are currently at low levels (and if kept low in the future), there are good opportunities for substantially increasing acacia production with modest investments in research and extension to support improved site management.

The potential productivity of eucalypt plantations in SE Asia is not yet clear. There are, as noted above, no experimental studies evaluating a range of management practices over successive rotations, against which operational productivity can be benchmarked. Productivity in commercial plantation estates ranged from 15–23 m^3 ha^{-1} y^{-1}. Several site and soil management practices currently practised in a number of subregions may hinder the prospects for higher production, unless they are improved.

The current growth rates are highly variable within subregions and at smaller scales within individual management units. Such spatial variability has not yet been explained in biophysical terms. However, the inventory systems of some companies should be able to include additional information to commence this type of analysis. Spatial mapping of productivity and analysis of relationships between growth and site factors would provide key information for improving management.

6 Ways forward

This study is a review and synthesis of relevant scientific information to evaluate the prospects for sustainable wood production over multiple short-rotation acacia and eucalypt plantations in SE Asia. In addition to reviewing published literature and unpublished scientific reports, we visited all regions covered by the study and discussed issues with local managers and scientists. Many conclusions on management discussed here are influenced by their inputs and insights. A unique feature of the study was that collaborators provided commercially sensitive inventory data on wood production from major plantation estates, covering periods of up to two decades, for our independent analysis and interpretation. This level of data sharing for a common purpose is an important measure of cooperation and trust on their part. The wealth of data, and CSIRO's experience spanning two decades of collaborative research with a number of partners in all countries covered, have together enabled a review of the productivity of short-rotation acacia and eucalypt plantations in SE Asia that identifies critical issues constraining production and the main R&D priorities and operational challenges, and allows suggestions for ways forward.

We did not set out to audit forest management practices or to pass verdicts on outcomes, targeted to individual organisations or countries. However, our observations (Chapter 4) and the results of our analysis (Chapter 5) do lead us to comment on the merits and demerits of current practices, a core objective of this review.

Little research has been done locally on the impacts of a number of potentially damaging management practices (e.g. bulldozing for site preparation and repeated ploughing for weed control), so in such cases we have used relevant scientific principles to draw conclusions. Where local research is available it has been highlighted (e.g. Table 12, Figure 11).

There is an important point to note here. Prospects for, and challenges to, sustainability across SE Asia are as diverse as the biophysical attributes of the plantation ecosystems, prevailing investment models, current level of research and application, and cultural and social contexts unique to each country and indeed to different regions within countries. For further progress, each of the regions and in some cases local subregions, warrant separate strategies; there is no single generalised strategy applicable to all of SE Asia. Therefore readers are referred to the country-level analysis in Chapter 4 for more in-depth review of country-specific research and management challenges and ways forward.

In this chapter we summarise our observations, insights from discussions with local researchers and managers, and insights from the analysis of the inventory data and relevant research. We highlight key issues and suggest the ways forward. Where possible we have identified issues that are generic, but in other cases they are country-specific. We comment on ways to address them through strategic research and approaches to broad-scale application.

Towards sustainable production

There is strong evidence from some countries including Australia, Brazil, Chile, New Zealand, South Africa and the USA, that sustainably managed plantation forests provide high-quality wood over the long term with environmental care; serving the economy, environment and society. This is an achievable goal for SE Asia and warrants supportive policies and collaborative actions by both private investors and public agencies.

Experience from several decades of eucalypt plantation forestry backed by substantial research is available to managers in Brazil and South Africa, as well as for hybrid pine plantations in subtropical Australia. More than a century of experience is available to pine plantation managers in temperate regions. In comparison, short-rotation forestry in SE Asia is a young sector and many of the region's plantations were planted less than 10 years ago. The establishment of more than 7 million hectares of acacia and eucalypt plantations in less than two decades is a substantial achievement in building a renewable natural resource base. The plantations are already supporting rural economies and employment in the regions covered in this report. If managed sustainably, and if wood harvests are processed to add value locally, they can make even greater contributions to regional economies in the future.

Achieving sustainable production from acacias and eucalypts over successive rotations is an ongoing journey. It involves learning to deal with the challenges emerging in the plantation ecosystems. Sustainable production is facing some risks and there is an urgent need to better align ecosystem variables and processes (see Figure 1) for sustainability. The prevailing biophysical risks include: (i) poor harvesting and inter-rotation site management practices that are bound to deplete site resources essential for plantation growth, especially for eucalypts, and (ii) the rapid spread of fungal diseases causing mortality to *A. mangium* in Sumatra and Sabah. These risks, together with unrealistic expectations of increasing productivity from genetic improvement that is not supported by integrated management, pose the threat that industrial demand for wood will outstrip the capacity of plantations to supply it. This will lead in turn to overcutting or continued dependence for wood from unsustainable harvesting of remaining native forests.

An overriding issue heightening these risks is inadequate investment in research to understand and sustainably manage plantation productivity.

Inventory data are more than a stocktake; they can be a knowledge base for understanding productivity in space and time

There are two broad types of plantation forest growers: large integrated companies that grow wood for their own processing factories, and smaller growers who sell wood to industry, either directly or via wood traders. At present, most growers see the purpose of inventory as simply a stocktake of harvestable wood available for the coming year or years. This is an important but narrow purpose. Accurate inventory data that are well captured, organised and readily retrievable, together with corresponding information on biophysical attributes and management practices, create a database that can be central to supporting and assessing sustainable production. Appropriately analysed, they can lead to an understanding of how productivity is varying in space and time. This in turn can help managers set production goals and direct research investments towards those constraints on production for which the best returns are likely.

The almost universal absence of a systematic network of permanent sample plots maintained over successive rotations, and the consequent inability to trace the history of sampling points (or compartments), limits the interpretations of productivity trends for successive crops, either replanted or coppiced. For growers who maintain inventory databases, this can be corrected in future with some well thought out additional effort. Special attention is warranted to support smallholders who manage a few hectares of plantation and cannot afford to maintain inventory systems; they need support from allied companies or government agencies.

It is not yet possible to realistically benchmark the current productivity of eucalypt plantations in SE Asia against measures of potential productivity, within or between regions. Preliminary benchmarks are possible for *A. mangium* in Sumatra and acacias in Vietnam, as there are experimental studies that show potential productivity (Chapter 4). Without such information, productivity goals are often set unrealistically by corporate managers driven by expectations of achieving the high MAIs reported from the fast-growing Brazilian eucalypt plantations on sites with high productive capacity where system management has been backed by substantial research. This situation can be improved by establishing, on an ongoing basis in representative land units, experimental/demonstration trials that test a small set of best-bet options for integrated management with appropriately selected improved germplasm, together with the current practices as control treatments. This will enable the evaluation of site productivity potential on an ongoing basis. Such studies can serve multiple purposes: demonstrate what is possible, provide information for realistic goal setting, guide management and improve understanding of local constraints from a scientific perspective.

One consistent result from the yield analysis in Chapter 5, applicable to all ecosystems and species, is the high variability in growth rates (MAI) at various scales. This is highlighted by the high coefficients of variation, often exceeding 40% for 0.05 ha inventory plots and 30% for blocks or compartments within subregions. Our field observations also confirmed high variation in growth, even within small land units in many cases. Variation in growth rates, as measured by inventory, across an estate is to be expected in commercial forestry and is usually accounted for as differences in Site Quality (SQ) or Site Index (SI). For second-rotation acacia plantations in Indonesia and Malaysia, and first-rotation *E. pellita* in Indonesia, a major reason for this variability is disease attack. Elsewhere, for example in eucalypt plantations in China, diseases and pests are not the major cause of such variation. Rather, it seems to arise from variation in site quality and management inputs.

The point we emphasise here is not the extent of variation per se (although it surely needs attention) but the current lack of information about factors that govern growth rates and their variation in the landscape. For example, Figures 14–16 and 21 (Chapter 5) show the distribution of widely differing MAI classes for hundreds of inventory plots within subregions managed by single organisations. This raises questions about the spatial distribution of stand productivity. For example, are low-productivity or high-productivity stands confined to specific parts of the estate, or to particular terrain types, soils, tree genotypes, diseases or management histories? Are such factors, if they can be determined, common over rotations? If landscapes can be thus delineated, attempts to seek solutions through research and operations would become more feasible and effective.

Inventory data should be recognised and managed not just as a routine stocktake of available wood but as a repository of key information about site conditions and stand productivity essential for contemporary management.

The inter-rotation management phase is a window of risk and opportunity for short-rotation forestry and is central to sustainable production

Planting of unsuitable or unimproved genetic material can reduce productivity and render the plantations susceptible to diseases and pests (Section 3.1), but it does not necessarily damage site potential beyond that rotation; it can be corrected by changing to better planting material. In contrast, poor harvesting and subsequent management practices that deplete or damage soil leave behind legacies of degraded sites, environmental damage such as soil erosion, and reduced productive capacity. A site can be damaged in a single day by bulldozing soil and burning organic matter, with consequences that may be irreversible (Photo 19). Restoration of the productive capacity, if at all possible, will be costly and may take decades. During the short life of the crop there is no scope and time to correct the consequences of mismanagement that occurred prior to its planting. Thus, as discussed in Chapter 3, inter-rotation management is a defining phase—a window of risk and opportunity—for the success of short-rotation forestry.

There is an urgent need for applied, adaptive research to underpin inter-rotation management for sustainable production. Ideally, this research should be undertaken in collaborative partnerships involving researchers and plantation managers, to improve the knowledge and practices related to this critical management phase. Small growers require special consideration, both in terms of the inputs they can afford and improvements to inter-rotation management that they can adopt. The key components should include management of harvesting systems practices, site management, and vegetation management during the establishment phase. These are elaborated below.

Harvesting practices should be in harmony with the biophysical attributes of sites and aim to achieve minimum site disturbance

One of the common reasons for poor management outcomes is the disconnect between harvesting that has the goal of getting wood on the truck at the lowest unit cost, and subsequent site preparation for the next crop that has the goal of replanting at the lowest cost per hectare. Treating them as unrelated activities (run in some cases as separately costed businesses), each with its narrow goal, results in damaging practices. We found very little evaluation of the current and different harvesting systems and their biophysical outcomes in plantation forests in the regions. Yet, significant improvements in harvesting operations are warranted, especially on steep terrain in the humid tropics (Photo 12) and on steep terrain in China and elsewhere (Photo 27). Exclusive focus on unit cost determined by short-term budgets and the disconnect between harvesting decisions and subsequent pre-planting requirements have been common causes of site-damaging harvesting practices in other regions. Harvesting practices should conserve site resources and facilitate the subsequent steps towards good site preparation and planting. Examples of good practices can also be found in SE Asia (Photos 5, 6). Site preparation should not be seen as repairing the damage imposed by poor harvesting practices.

An integrated approach is needed, with the goals of site sustainability shared and jointly achieved by those planning and leading harvesting and subsequent site management.

Site management should conserve site resources

In plantation forestry, sustainable production does not have to be achieved with any single species in perpetuity, just as we do not expect long-term production of successive rotations from a particular provenance or clone. Changing from one species to another or planting more than one species in different parts of one estate, in response to biological threats or commercial opportunities, are logical management decisions. This is happening in Sumatra today, where *E. pellita* is replacing *A. mangium*, and happened in Vietnam a decade or so ago when acacias replaced *E. camaldulensis*.

However, it is important to recognise that such actions can be taken promptly and effectively only if the soil properties and landscape values have been maintained or enhanced along the way with science-based and holistic management (so that the ecosystem can be productive with a range of species). Thus slash and litter burning may be a cheap and easy option, but has long-term impacts including losses in production and soil erosion.

Whole-tree harvesting, including stump extraction, is becoming popular to provide fuel for bioenergy, without any information on the impacts of such intensive harvests on loss of organic matter, nutrient depletion and soil properties. These practices impose on subsequent users of the land the near impossible task of replacing the losses of organic matter and nutrients. Harvesting the entire biomass at short intervals is likely to be a false route to sustainability on many soil types. Management practices that conserve site resources and minimise disturbance to the site are essential (and a priority) to set the framework for increasing and sustaining production in a cost-effective and environmentally prudent way (Chapter 3).

Given the potential export and loss of soil nutrient stock, it would be valuable to invest in research aimed at understanding the nutrient dynamics in these systems under different management practices and developing appropriate site-specific management practices and more judicious fertiliser application strategies. This is especially important for eucalypts, for which the nitrogen economy will require closer attention.

Judicious management of vegetation for meeting production and environmental goals

Commercially viable growth rates in plantation forestry cannot be achieved without vegetation (weed) control. Yet, weed management practices have not moved beyond manual control for decades in several regions, while in Thailand, southern Vietnam and parts of China managers see repeated ploughing as an imperative without evaluating herbicide use as an alternative (Chapter 4). In Section 3.3, we discussed why sole reliance on repeated ploughing is an ineffective way to control competition between trees and weeds, and is likely to reduce wood yields and degrade critical soil properties.

In contrast, companies in Sumatra and Kalimantan have adopted herbicide technology, but the ‘zero weed tolerance’ some insist on is a carryover from the methods used in oil palm and rubber plantations, and of questionable value for forestry. One study in southern Vietnam (Section 4.3) showed that there is scope for developing optimal weed management strategies with no tillage and modest use of herbicides (Photos 23 and 24).

Contemporary practices for weed control support neither repeated ploughing nor blanket, ‘zero weed’ policies that eliminate understorey throughout the rotation. It is relatively easy to develop a vegetation management practice to achieve production goals without environmental harm.

Research aimed at developing judicious herbicide technology for weed control in plantations would support both productivity and fire-prevention goals.

Managing available water for production

There is little information on the critical variables determining the quantum of available water (broadly determined by the amount and distribution of rainfall, evaporation and fundamental physical attributes of soil) and productivity of key genotypes planted in the region. The evidence from both temperate and tropical zones is that plant-available water can be an overriding site variable determining growth rates and sometimes mortality in areas with seasonal water deficit. It is a common observation that in southern Vietnam *A. auriculiformis* ceases diameter growth for 2–3 months in the annual dry season, even in deep soils and where weeds are well controlled. Many soils allocated to plantation forestry in SE Asia are shallow; if management leads to losses of surface soil and soil organic matter and degradation of soil structure, water available to the plantations will also be reduced.

At many sites (see Chapter 4) repeated ploughing would sever roots to a depth of 30 cm, two to three times per year, reducing fine root access to the soil. In addition, soil damage may reduce water infiltration.

These observations suggest that research is warranted to understand the factors determining available soil water and its relationship with growth at contrasting sites within the estates of each grower organisation to improve site-specific management, especially in seasonally dry environments.

Risk management

Here we will discuss two key risks: fire, and diseases and pests.

Preventing fire outbreaks

The risk of fire outbreaks is a concern dominating managers' thinking at a number of locations. While there is some fire surveillance by companies, the main response to fire risk in some regions is to reduce fuel loads by repeated ploughing, every year. There are several social and community factors allegedly responsible for ignition. In order to improve fire management, systematic information is needed on the frequency, extent and reasons for fire events. Establishment of fire breaks around plantation perimeters close to transport routes (often the starting points of fires), dialogue with workers and communities, training of workers (for example, no smoking at work) and other measures have succeeded in reducing fire risk and damage elsewhere. The sole dependence on repeated ploughing may maintain the status quo of fire frequency but will likely degrade sites, negating the overall objective of management that is to protect and improve wood production. Development of vegetation-control protocols with judicious herbicide use would therefore serve a dual purpose.

Managing diseases and pests

Diseases are a threat to plantation wood production in SE Asia (Chapter 4). Root rot and stem wilt/canker have led to a species change from *A. mangium* to eucalypts in Sumatra and parts of Sabah. Similarly, leaf blight diseases have destroyed large areas of eucalypt plantations in Thailand and Vietnam and led to a change from *E. camaldulensis* to acacias in wetter parts of southern and central Vietnam a decade ago. In Sumatra and Sabah, the change in species seems likely to reduce growth rates, at least in the short term. In comparison, a change from eucalypts to acacia in response to disease has probably increased wood production in Vietnam, as indicated by the relative productivity of the two genera in trials.

Many eucalypt plantations in SE Asia face production losses from gall wasp attack. However, given effective research, planting more resistant genotypes together with effective biological control should substantially reduce the impact of this pest.

Undoubtedly, new challenges from diseases and pests will emerge. Quarantine measures may slow, but are unlikely to stop, the entry of diseases and insects. Some fungal diseases already present are likely to increase their impact as plantations expand. An example here is *Ceratocystis*; apart from acacias in Sumatra and Sabah, it is a threat to eucalypts in Brazil, and now a potentially grave threat to acacia in Vietnam. Furthermore, pathogens evolve continuously, so their virulence may increase.

Eucalypts in Brazil and South Africa have faced disease and pest challenges, yet plantation productivity has improved in these countries over the decades.

Breeding options and priorities

SE Asian countries in general have invested in breeding programs that have identified suitable species and hybrids for each subregion and produced improved varieties. These improvements would have contributed to the current levels of productivity (Chapter 5). The contributions to disease and insect resistance brought about by changing to more resistant species or hybrids have been particularly important in some cases.

While breeding to further improve growth rates, stem form and wood quality remains important, producing genotypes that have resistance to major diseases and insects appears a more urgent goal for the future than increasing growth rates per se. Thus effort should emphasise plantation protection. Breeding needs to be linked with local pathology and entomology research. For example, it seems better to plan and breed for the arrival of a severe threat such as eucalypt rust, *Puccinia psidii*, than just to hope that it will not reach SE Asia. Resistant varieties are particularly important for poor smallholder farmers, who cannot afford to lose their crops.

For some subregions, there is also a need to improve resistance to climatic threats, notably wind damage from typhoons and storms, and cold snaps. Varieties adapted to predicted changes in climates will be needed, although producing them does not require a fundamental change in the breeding approach.

Conservation of and access to the genetic resources embodied in the wide original in-country base populations of the main acacia and eucalypt species (Table 6), with new additions from the species' natural ranges as required, are vital for ongoing breeding. It is an essential insurance to underpin sustainability.

Research base, coordination and collaboration

We have identified major risks and opportunities for advancing sustainable plantation forestry and have highlighted the core themes that we hope will help the deliberations of local organisations and companies. This study was not designed to review research capacity or R&D organisational arrangements in the countries involved. But as we progressed, it became clear that an overriding issue likely to affect future production is the lack of adequate investment and collaboration in research to understand and manage plantation productivity sustainably.

Large companies have R&D capacity, outcomes from which are understandably safeguarded as company intellectual property. We are not in a position to make comments on how well their efforts match the challenges they face. Information available to us did not suggest that the issues highlighted here are being tackled at sufficient depth. Beyond these players, overall R&D efforts, in quantity and quality, appeared weak or non-existent in several countries as discussed in Chapter 4. For example, many companies have a commitment to use genetically improved planting material, which is important, but spend very little effort gathering even simple information for improving management. Therefore, it is questionable whether the projected genetic gains are ever realised operationally. Genetic improvement is seen as a panacea, and there is a lack of understanding that breeding cannot overcome the damage inflicted to sites by short-sighted management practices.

In all locations, evidence of serious research contributions to sustainable productivity by public institutions was rare. Some public institutions that once did research on productivity have largely withdrawn from such work, on the premise that it is the business of companies and they should pay for it fully. One consequence of this is that public institutions with relevant skills and facilities are starved for operational funds, lose focus, and may become irrelevant to the sector and unable to provide appropriate policy advice to governments. This is a path to further deterioration, erosion of skills and lost opportunities for forestry.

We suggest below some important R&D areas (not ranked in priority) that are most amenable to collaborative efforts.

Site management research for southern China

The China Eucalypt Breeding Alliance is now in operation and an important initiative including public and private members. Can this be extended to a program aimed at improving sustainable management? We have pointed out that the regions need to substantially improve R&D and commitment to integrated, holistic ecosystem management. Research to address the core biophysical components of this problem can be worked out in a joint exercise by collaborators and then a network project can be established with clear goals and shared funding arrangements. The CIFOR network (see Nambiar 2008) might be a model for a southern China network of sustainable plantation forest management.

Vegetation management research for Thailand

The current vegetation management practices depending solely on repeated ploughing are not an efficient way to control weeds for enhancing production, or for managing vegetation for fire prevention. Research aimed at developing a judicious vegetation management strategy including herbicides would be ideal for initiating a collaborative program. Other key issues can be added over time, including the effects of bioenergy harvesting on carbon and nutrient flows and productivity.

Management of fungal diseases of A. mangium *in Sumatra*

This is an urgent and vexed problem demanding an early solution. The ecology, rate of spread, and agents and pests causing the wounding (monkeys and squirrels) are not confined to ownership of an estate, and thus future management has to be at the regional level. Research on biological control is complex and expensive and will be more effective if resources are pooled. Surveillance programs clearly have to be coordinated at the national level in order to be effective, as do quarantine regulations and policing. Breeding to screen for and improve disease resistance could also be more effective with collaboration across companies. Some collaboration is underway in Sumatra and discussions are underway in Sabah and Sarawak. A well-coordinated collaborative program supported by both private and public organisations would be a strong base for addressing this immense challenge.

Biocontrol and breeding to control the eucalypt gall wasp

The eucalypt gall wasp has emerged as a major threat to eucalypt plantation productivity in several SE Asian countries. Research to combat this problem is needed, with a combination of two approaches: biocontrol, and breeding and deployment of more resistant planting material.

A multicountry collaborative approach is warranted, as the problem extends across the borders of several neighbouring countries that exchange eucalpyt germplasm including Thailand, Laos, Cambodia, Vietnam and China.

Site and stand management for acacia and eucalypts in Vietnam

As noted earlier, Vietnam has strong and systematically planned breeding programs and these should be fostered with strong emphasis on breeding to minimise risk. But the future of increasing and sustaining plantation forestry in Vietnam hinges on: (i) development of systematic process-based research on and application of soil, site and stand management practices, coupled with adaptive demonstrations; and (ii) reinforcing surveillance and disease management for resource protection. The record of applying research in partnership with growers remains weak; so also are the linkages between public and private institutions in forestry business. Traditional 'silvicultural' research is old and static in its approach and is not abreast of contemporary science. In contrast to the situation in Indonesia, given the absence of R&D by large companies, Vietnam needs to develop innovative ways to develop and strengthen a prioritised research agenda.

The country has a special opportunity to promote its smallholder sector. Smallholders, who manage on average less than 5 hectares of plantation per family holding, have been allocated 46% of the land allocated to forest plantations in Vietnam (Blyth and Son 2014). These growers, many of them poor, make major contributions to national wood supply and the rural economy. Despite this, there is no coherent analysis of the productivity of their plantations, or their needs in terms of technical knowledge, access to inputs and fair marketing of their produce. The absence of coherent research and extension plans and their implementation to support the numerous smallholder growers in countries such as Vietnam to improve their productivity is a lost opportunity to improve livelihoods and rural economic growth.

Some broader considerations

Beyond the range of scientific aspects discussed in this report, broader changes are required at the institutional level to guide plantation forestry in SE Asia to a more robust sustainability path with improved outcomes. This review was not designed to provide R&D strategies for each of the participating regions. But we offer these general observations, as examples of important constraints that should be addressed in future R&D strategies.

Global evidence is clear: nations that have advanced with sustainable forestry have done so on the foundation of mutually supportive partnerships between private and public institutions. This partnership is not evident in SE Asia. Changes needed to advance sustainable productivity in SE Asia will not be easy, nor are there fixed guiding principles, because as noted earlier each country has its own unique circumstances and culture.

Some government research agencies consider that research on productivity is the business of the companies that make the profit and and that public agencies should focus on 'public good science' that excludes research on productivity. This is, in our view, outdated thinking that blocks the development of essential public–private partnerships. Leaders of public and private organisations must take joint responsibility for setting and implementing a new collaborative agenda for sustainability. Approaches required to make impacts within large companies are very different from those most needed by small growers, who, as an important part of the private sector in several SE Asian countries, need packages of basic technical assistance tailored to their needs and capabilities, as well as support for ensuring fair marketing of their wood.

It is essential for researchers to widen their understanding and forge linkages across disciplines. Research to sustain production transcends individual disciplines such as breeding, tree physiology, pathology, soil science, vegetation and fire management, harvesting, and operations research. Interdisciplinary teams are not easy to set up but are essential. Furthermore, all applied research must be better linked to operational management (inside or outside the organisations) so that research outcomes are adequately tested and validated at the operational level to gain the confidence of managers. Lack of such validation is a common reason limiting the application of R&D within a company. Too often subgroups in R&D tend to see productivity as 'somebody else's problem'—when it should be everybody's goal. Sustainable productivity must be seen as the criterion by which R&D is assessed.

In summary, the history of plantation forestry teaches us that sustainable plantation forestry is achieved not by any single solution but through systematic and continuous application of an integrated package of practices over time. Increasing and sustaining production is not operationally achievable in quantum leaps; it is achieved in incremental steps, at best. This requires a strong underpinning R&D capacity designed to address local/regional issues in which researchers and managers work in close partnerships bound by a strong culture of application and making positive and measurable impacts.

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