Australian Government

Australian Centre for International Agricultural Research

Water use and water productivity of *Eucalyptus* plantations in South-East Asia

ACIAR TECHNICAL REPORTS 89

Research that works for developing countries and Australia

Water use and water productivity of *Eucalyptus* plantations in South-East Asia

Don A White, Michael Battaglia, Shiqi Ren and Daniel S Mendham

ACIAR
Research that works for developing countries and Australia
aciar.gov.au

2016

The Australian Centre for International Agricultural Research (ACIAR) was established in June 1982 by an Act of the Australian Parliament. ACIAR operates as part of Australia's international development cooperation program, with a mission to achieve more productive and sustainable agricultural systems, for the benefit of developing countries and Australia. It commissions collaborative research between Australian and developing-country researchers in areas where Australia has special research competence. It also administers Australia's contribution to the International Agricultural Research Centres.

Where trade names are used this constitutes neither endorsement of nor discrimination against any product by ACIAR.

ACIAR TECHNICAL REPORTS SERIES

This series of publications contains technical information resulting from ACIAR-supported programs, projects and workshops (for which proceedings are not published), reports on Centre-supported fact-finding studies, or reports on other topics resulting from ACIAR activities. Publications in the series are distributed internationally to selected individuals and scientific institutions, and are also available from ACIAR's website at <aciar.gov.au>.

White D.A, Battaglia M., Ren S. and Mendham D.S. 2016. Water use and water productivity of *Eucalyptus* plantations in South-East Asia. ACIAR Technical Reports Series No. 89. Australian Centre for International Agricultural Research: Canberra. 55pp.

ACIAR Technical Reports – ISSN 0816-7923 (print), ISSN 1447-0918 (online)

ISBN 978 1 925436 34 1 (print)
ISBN 978 1 925436 35 8 (PDF)

Technical editing by Kate Langford
Design by Peter Nolan, Canberra
Printing by Bytes 'n Colours, Canberra

Cover: *Eucalyptus urophylla* × *camaldulesis* with wide spacing between rows and with four rows of recently planted cassava.

Foreword

For three decades, the Australian Centre for International Agricultural Research (ACIAR) has supported research on the domestication, improvement and management of *Eucalyptus* and Acacia species for plantation forestry, including aspects of the sustainability of these plantations, such as the protection of soil and water resources.

Eucalyptus plantations make an increasingly important contribution to meeting the global demand for wood products as well as to smallholder livelihoods. China has more than 2.6 Mha of these plantations and there is another 1.6 Mha in South-East Asian countries. These plantations also deliver important ecosystem services, for example by reducing erosion, and enabling countries to protect remnant natural forest while meeting their demand for wood products.

While the growth of plantations has generally been a positive development, concerns are being raised in many countries about their water use and impact on stream flows. Often these concerns are not based on good science, nor do they take account of the water use from alternative land uses. While there has been a lot of research globally on quantifying water use by plantations and alternative land uses at both the catchment and plot scale, very little of the data is from tropical climates, and even less is from South-East Asia or southern China.

This report reviews the state of knowledge on water use by *Eucalyptus* plantations in South-East Asia and provides some analysis of what it means for plantation water use in the different climatic zones where these plantations are being established. It aims to support local land and water resource decision makers in southern China, Laos, Thailand, Indonesia, Vietnam, Cambodia and Myanmar by synthesizing current knowledge into a simple, easy to use tool.

This report makes a significant contribution to the ongoing global effort to provide good science to support sustainable natural resource management. This is achieved by:

- establishing general principles of evaporation from vegetated land and quantifying the broad differences between wood production plantations and the main alternative land uses, including natural forest.
- developing a simple model of water use by *Eucalyptus* and alternatives, and incorporating these models in a spreadsheet-based water use tool for South-East Asia.
- applying this 'tool' to quantify water use by *Eucalyptus* plantations in the main plantation growing regions of South-East Asia.

Nick Austin
Chief Executive Officer, ACIAR

Contents

Acknowledgements

This report was completed as part of ACIAR project FST/2014/016 (*Water use by Eucalyptus in plantations—sustaining a social licence in South-East Asia)*. Local contextual information was compiled during two trips to South-East Asia and southern China. These trips were supported by local contacts. Dr Roger Arnold of the Chinese Eucalypt Research Centre hosted two trips to Guangdong and Guangxi provinces in China. Mr Stephen Midgley of Salwood Asia Pacific Pty Ltd travelled to Laos to accompany the lead author at many meetings and on a field trip to the plantation areas between Savannakhet and Xepong. Mr Khamphone Mounlamai organised two workshops at the National Agricultural and Forest Research Institute (NAFRI) in Vientiane, Laos. Dr Tran Lam Dong at the Vietnamese Academy of Forest Sciences (VAFS) also hosted two visits to Hanoi and a trip to central Vietnam. Mr Jetsada Wongprom (Kasetsart University, Bangkok) hosted a visit to plantation areas to the north-east of Bangkok.

The staff from local forestry enterprises, research institutes, government departments and plantation companies was always helpful. A number of seminars were given to plantation growers, government officials, researchers and management and staff at Stora-Enso in Laos and Guangxi, Birla in Laos, Burapha in Laos, NAFRI in Laos, VAFS in Hanoi, Chinese Eucalypt Research Centre in Guangdong Province China and Kasetsart University in Thailand. Suan Kitti Ltd in Thailand supported these seminars by attending and providing feedback on the content and presentation. Researchers and managers from these organisations also provided helpful comments on drafts of this report.

The authors are indebted to the many local people who took the time to meet with them and drive them to field sites. Their insight into the business and governance of plantation forestry in South-East Asia was invaluable. It is hoped that this report justifies the time invested and assists all of those with an interest in plantation forestry in South-East Asia to manage plantations and water resources.

There are countless people who have shared their knowledge and experience with the authors and allowed them to test their ideas. These people are too numerous to list but the following deserve special mention: Dr Michael Ryan (Colorado State University), Dr Philip Polglase (CSIRO), Dr Sadanandan Nambiar (CSIRO), Dr Chris Harwood (CSIRO), Dr Chris Beadle (CSIRO and Tasmanian Institute of Agricultural Research), Dr Jenny Carter (Rio Tinto), Dr Richard Silberstein (HydroEnviro Pty Ltd), Dr Gordon Duff (University of Tasmania) and Dr John McGrath (McGrath Consulting).

Drs Chris Harwood and Michael Battaglia reviewed and edited several drafts of this report. Mr Tony Bartlett, Forestry Research Program Manager with ACIAR, also made a number of useful suggestions for improvements.

Authors

Don A White (corresponding author)

National Centre for Future Forest Industries, School of Plant Science, University of Tasmania, College Road, Sandy Bay, Tasmania 7001, Australia

School of Veterinary and Life Sciences, Murdoch University, Murdoch, Western Australia 6150, Australia

Whitegum Forest and Natural Resources, PO Box 3269, Midland, Western Australia 6056, Australia

Email: <whitegumfnrm@gmail.com>.

Michael Battaglia
CSIRO Agriculture, Private Bag 12, Hobart 7001, Australia

Shiqi Ren
Guangxi Forestry Research Institute, 23 Yongwu Road, Nanning, Guangxi 530002, China

Daniel S Mendham
CSIRO Land and Water Flagship, Private Bag 12, Hobart 7001, Australia

Glossary

Symbol or acronym	Name or full text	Description	Units (if applicable)
E_t	Evapotranspiration	Total evaporation from a vegetated land surface; the sum of transpiration by vegetation, canopy interception and evaporation from the soil.	mm
E_0	Potential evaporation; reference evaporation	Maximum energy limited rate of evaporation.	mm
k	Crop factor	The ratio of evapotranspiration to potential evaporation.	Dimensionless
CWI	Climate Wetness Index	Ratio of rainfall to potential evaporation.	Dimensionless
PWP_{WOOD}	Plantation Water Productivity	Wood production per unit of evapotranspiration.	g kg^{-1} tonnes ML^{-1}
T_{TREE}	Crop tree transpiration	The evaporation, through the leaf surface, of water that has been taken up from the soil by roots and transported to the leaves via stem and branches.	mm
S	Soil evaporation	Evaporation from the soil surface.	mm
T_{WEED}	Weed transpiration		mm
I	Interception	Rainfall that is intercepted by the canopy and evaporates without reaching the ground.	mm
FAO	Food and Agriculture Organisation of the United Nations		
FAO-56	A measure of reference evaporation developed by Allen et al. (1998) for the FAO	Reference evaporation calculated using the Penman-Monteith equation (Monteith 1965) for a 0.12 m tall grass with constant conductance and albedo (reflectance).	mm
α	Albedo (Latin for white)	Proportion of incident radiation that is reflected by a surface; light coloured objects have high albedo.	Dimensionless
R_n	Net radiation	Amount of total radiation absorbed by a surface.	W m^{-2}
s		Slope of the relationship between saturated vapor pressure and temperature.	kPa °C^{-1}

continued…

Symbol or acronym	Name or full text	Description	Units (if applicable)
γ	Psychrometric constant	The slope of the relationship between the partial pressure of water vapour in air and temperature	kPa °C^{-1}
c	Empirical catchment parameter	Parameter in model of Zhang et al. (2004) (Equation 6). This empirical constant integrates the effects of sources of variation, other than climate wetness index, on the crop factor. It is significantly different for annual pastures, natural forests and plantations.	Dimensionless
P	Rainfall		mm
LAI	Leaf Area Index	The ratio of single-sided leaf area to ground area.	Dimensionless
W	Relative plant-available soil water content	The proportion of the maximum possible soil water storage that is still available to plants.	Dimensionless
a_w		The slope of the linear portion of the relationship between the crop factor and relative plant-available soil water content.	Dimensionless
W_0		The value of relative plant-available soil water content (w, Equation 7) for which the crop factor is 0.5.	Dimensionless
W	Wood yield		tonnes ha^{-1}
TE_{DM}	Transpiration efficiency	The amount of dry matter produced per unit of water transpired by the crop trees.	g DM kg^{-1} H_2O
HI	Harvest index	Proportion of the total dry matter produced that is allocated to wood.	g g^{-1}

Executive summary

Plantations of tropical *Eucalyptus* and *Acacia* species are important contributors to the economy in Vietnam, China, Indonesia, Malaysia and Thailand. Similar potential exists in Laos, Cambodia and Myanmar (Harwood and Nambiar 2014). The sustainability of these plantations is a subject of ongoing debate in the region. Harwood and Nambiar (2014) demonstrated that, by application of best practice, the productivity of these plantations could be sustained, and in most cases increased, over successive rotations.

One aspect of sustainability that was not addressed by Harwood and Nambiar (2014) was water use. *Eucalyptus* plantations have developed a singular reputation for 'excessive' rates of water use, although there has been little research on this issue in tropical locations. Land-use decisions are rightly made locally, and this report aims to help land and water managers make decisions based on knowledge rather than on perceptions.

Although water use by plantations is situation specific, there are principles that can guide understanding and assist in land-use and water resource planning. This report presents these principles and tests and applies them in the South-East Asian context. Rather than provide definitive statements about the importance of water use by *Eucalyptus* plantations, it aims to provide a scientific basis for local decision making.

Section 1: Important concepts and definitions

Several key concepts are introduced and defined. These concepts must be understood in order to interpret the analysis of plantation water use presented in Sections 2 to 5.

a. Evapotranspiration or total plantation water use is the sum of direct water use by the trees, canopy interception and evaporation from the soil surface.
b. Potential evaporation (also called reference evaporation) is the maximum energy limited rate of evaporation.
c. The crop factor is the ratio of evapotranspiration to potential evaporation.
d. The climate wetness index is the ratio of rainfall to potential evaporation.

This report aims to assist with quantitative assessment of water use and stream flow. It does not address the broader issue of water security, which has biophysical and social dimensions.

When quantifying water use by plantations or any other land use, it is important to include all of the evaporative fluxes from the land. Many studies that compare water use by alternative land uses only consider transpiration, which may be as little as a third of total evapotranspiration. This approach tends to exaggerate the differences between *Eucalyptus* plantations and alternative land uses.

Water use is very strongly climate dependent. The crop factor and climate wetness index are normalised with respect to potential evaporation. The crop factor is an objective, climate-adjusted measure of vegetation water use that is used in most of the analyses in this report.

Section 2: Water and energy limits to plantation water use

This section describes the absolute energy and water limits to plantation water use. These concepts are incorporated in the simple model of Zhang et al. (2004). This model predicts the crop factor as a function of the climate wetness index and a catchment parameter that has been derived for different land uses. Using this model, the following is demonstrated.

a. When the climate wetness index is greater than 1.5, the predicted annual run-off from all land uses is very large. This applies to large parts of South-East Asia, including northern Vietnam, northern Laos, southern Thailand, Sumatra, Kalimantan, western Java, Malaysia, Guangdong province and southern Guangxi province.

b. The greatest proportional effect of land use on evapotranspiration occurs where the climate wetness index is between 0.7 and 1.3. This applies to northern and central Thailand, southern Laos, central Vietnam and much of Cambodia and Myanmar.

Important limitations of this analysis are also discussed.

a. The effect of planting on stream flow will vary depending on which part of the catchment is planted. For example, planting wet areas will have a greater impact per area planted than planting ridge-top locations.
b. This approach does not account for variation in evapotranspiration with plantation age. Immediately after harvest, and prior to canopy closure, evapotranspiration will be less than from a plantation after canopy closure.
c. Although this analysis suggests that in a lot of South-East Asia, plantations may not have an important effect on annual stream flow, it does not consider seasonal variation in flow, and in particular does not quantify changes in low- or dry-season flow due to plantation establishment.

Section 3: Seasonal variation in water use by plantations of *Eucalyptus* and alternative crops

Many regions in South-East Asia have a pronounced dry season, during which rainfall is much less than potential evaporation. In areas with an extended dry season (longer than two or three months) steady state models of water use, based on global data sets, will overestimate water use by plantations. These models do not account for periods where soil drying results in an increase in resistance to evaporation due to stomatal closure and leaf shedding.

Using a combination of published results for temperate *Eucalyptus* plantations and published and unpublished data from southern China, a simple tool has been developed for estimating annual and monthly water use by tropical *Eucalyptus* plantations. This tool is based on a model of the crop factor that was developed using published and unpublished data from southern China. The tool was used to predict *Eucalyptus* plantation water use for selected locations representative of the major plantation regions in South-East Asia.

This analysis showed that variation in the evapotranspiration and the crop factor as a function of available water is very similar for temperate *E. globulus* and tropical *E. urophylla* plantations. This increases our confidence in the generality of the simple tool used here to quantify water use by *Eucalyptus* plantations in South-East Asia.

Section 4: Water use by *Eucalyptus* plantations in South-East Asia

The tool developed in Section 3 was used to quantify water use by plantations in all of South-East Asia, with a particular emphasis on those areas where the crop factor is between 0.7 and 1.3. For this analysis, the plantation regions are grouped according to Koppen climate types rather than country. This is because water use is climate dependent and climate may vary more within than between countries. For example, the climate in northern Laos is more similar to that of northern Vietnam and southern Guangxi than it is to that of southern Laos.

The areas identified in Section 2 as having a climate wetness index between 0.7 and 1.3 are all in the Equatorial Savanna or Warm Temperate climate types. In all of these areas, predicted water use by *Eucalyptus* plantations was less than 70% of rainfall in 95% of years. Our simple model predicted that for one in every 10 years in central Guangxi, predicted evapotranspiration was more than 90% of rainfall. Even in this situation, predicted annual contribution to stream flow was greater than 150 mm.

This report concludes that *Eucalyptus* plantations will not have an important effect on annual stream flow in large primary catchments in South-East Asia and China. However, it must be noted that the effects of *Eucalyptus* plantations on dry-season flow have not been determined with enough precision to quantify the effect of *Eucalyptus* plantations on low flows, particularly in small tertiary or quaternary catchments.

Eucalyptus plantations are deep-rooted perennial crops with an indeterminate growth habit. These characteristics result in slightly higher water use by *Eucalyptus* plantations than by alternative land uses. This difference occurs in the early dry season and whenever the dry season is broken by a large rainfall event. The key times when *Eucalyptus* water use is likely to differ most from that of alternative land uses, and for management to reduce the water impacts, are the transition from the wet to the dry season and late in the dry season. Most studies of crops focus on the wet season, and most measurements in *Eucalyptus* plantations focus either on the wet or the dry season, and fail to recognise the importance of the transition between seasons.

Section 5: Plantation management in South-East Asia: water issues

Many plantations in South-East Asia are established as only a small proportion of catchment area. In Laos the total planted area is very small and the area per catchment is less than 5%. In contrast, some local catchments in southern China are planted with eucalypts from the ridge top to the valley bottom. If wet areas, such as streamside reserves are avoided, the proportional effect of plantations will be roughly equal to, or less than, the area-weighted effect calculated using the curves described by Zhang et al. (2004).

Agroforestry systems are common in South-East Asia and include single tree rows on paddy bunds in Thailand and interplanting with cassava and hill rice between widely spaced (9 m) rows of *Eucalyptus* in Laos. In both situations, the *Eucalyptus* trees have access to additional water compared to block plantings. In Thailand, this has been shown to result in increased transpiration per tree and increased water use efficiency in *Eucalyptus* (Wongprom 2012; Wongprom et al. 2012).

Vegetation management within plantations is a crucial issue for South-East Asia. Harwood and Nambiar (2014) highlighted the potential for cultivation (ploughing) to damage surface roots, increase erosion and destroy soil structure. However, uncontrolled, weeds will compete for water and may substantially reduce production and water productivity (wood production per unit of evapotranspiration) in plantations of *Eucalyptus*. This effect will be most important in the transition from the wet to the dry season. Vegetation management by means other than cultivation should at least be investigated as an option to protect both soil and water resources in South-East Asian plantations.

Section 6: Plantation water productivity

Water use alone is a very blunt instrument for making land-use decisions. Exploring the relationships among growth and water use highlights the importance of a multi-factor analysis and approach to land-use planning.

Wood production per unit of evapotranspiration (plantation water productivity) is determined by: the transpiration efficiency of dry-matter production; the proportional allocation of dry matter to wood; and the ratio of evaporative losses to transpiration. The variation in productivity and water use with climatic and site characteristics are complex and the subject of a vast amount of literature. This apparent complexity can be reduced to this simple statement: "managing plantations to maximise their growth will also maximise plantation water productivity at the stand scale". Reducing planted area, but selecting areas where water use is greatest, may be one option for managing the trade-off between wood production and water use at the catchment scale.

Introduction

In Australia, South Africa, Spain, Portugal and many developing countries the expansion of plantations of Australian tree species has been associated with concerns about their water use. Opposition to plantations due to concern about their water use has been strongest where eucalypts have been planted. The issue of water use by plantations of *Eucalyptus* species is now generating debate in new regions of plantation development including South-East Asia[1] (particularly in Vietnam, Laos, Thailand and southern China). The trend towards shorter rotations, together with climate change has heightened tensions in the community regarding the potential of *Eucalyptus* plantations to compromise water security.

There are now approximately 2.6 Mha of *Acacia* and more than 5 Mha of *Eucalyptus* plantations in South-East Asia (Harwood and Nambiar, 2014). In Malaysia, Indonesia and Vietnam, *Acacia* occupies more than 90% of the planted area. In Thailand and southern China *Eucalyptus* plantations dominate. In common with the experience in other parts of the world, the expansion of *Eucalyptus* plantations in South-East Asia has provoked debate and concern over water use, particularly in Guangdong province in China (Zhou et al. 2002) and Thailand (Wongprom et al. 2012). *Eucalyptus* plantations in Laos currently occupy less than 50 000 ha but a number of plantation companies are engaging with local and central government with a view to developing viable *Eucalyptus* plantation estates and associated processing facilities. In Laos, community and government concern over water use has resulted in a very cautious approach to the allocation of land for new plantations. In Indonesia, the area of *Eucalyptus* is likely to increase in the next decade as *Eucalyptus* plantations replace *Acacia* in areas where heart rot, root rot and stem canker diseases are severe (Harwood and Nambiar, 2014). There is a pressing need for data and tools for assessing the current and future water use of plantations in South-East Asia and China as part of water allocation and planning in the region.

Community attitudes to plantations of *Eucalyptus* species are reflected in the media. Eucalypts were recently described as "water pumping machines" in the Chinese media (CCTV2, Guangxi, August 26, 2015—"Guangxi Green Desert—Fast Growing Eucalypt Plantations"). This descriptor has not been restricted to the popular media; *Eucalyptus* and other tree species have also been described as pumps in the scientific literature (e.g. Tan et al. 2011). This is not an accurate description of the role that trees, or any other type of plant, play in the movement of water in the soil-plant-atmosphere continuum. Use of the word pump to describe *Eucalyptus* trees suggests that they generate the force that moves water from the soil to the atmosphere. This energy is actually provided by solar radiation, which generates temperature and pressure gradients between the air surrounding a tree and the moist air inside the leaves. In the literature that describes evaporation from the environment, the movement of water in the soil-plant-atmosphere continuum is often described using an electrical analogy in which trees and other plants act as variable resistors (Cowan, 1972). The colourful description of eucalypts as pumps is easily countered. However, the use of inaccurate terms by lobby groups and the media does not diminish the need for a careful and objective analysis of water use by *Eucalyptus* plantations.

Although there is very little scientific data on water use by eucalypts in South-East Asia, there is a good understanding of the general principles of water use by vegetation including by *Eucalyptus* in plantations. This understanding suggests that it is possible to manage plantations in the landscape to ensure water security and to increase wood production. There is a growing demand in South-East Asia and southern China for tools to enable an objective discussion of the effects

1 In this report South-East Asia refers to a region that includes Indonesia, the Philippines, East Timor, Vietnam, Cambodia, Myanmar, Laos, Thailand. Malaysia, southern China (Guangxi, Guangdong, Hainan and Fujian provinces).

of *Eucalyptus* plantations on water resources and to inform water and land-use planning in the region. This report synthesises the current knowledge on water use by *Eucalyptus* plantations and uses a simple tool that incorporates monthly and annual water balance models to estimate the water use of *Eucalyptus* plantations in different climatic zones.

Research on the water use by tropical and sub-tropical *Eucalyptus* plantations has occurred mostly in Brazil (e.g. Almeida et al. 2007; Stape et al. 2010) and China (e.g. Zhou et al. 2002; Lane et al. 2004). There has also been substantial work done in monsoonal south India (e.g. Roberts and Rosier, 1993; Calder et al. 1993) and limited studies in other locations including Thailand (Wongprom et al. 2012). In India, transpiration by *Eucalyptus* plantations generally exceeds that of alternative land uses (Calder et al. 1993). Lane et al (2004) concluded that *E. urophylla* plantations on the Leizhou Peninsula in southern China were unlikely to adversely affect water resources. In Brazil stream flow was reduced from 10% to only 3% of rainfall in a catchment planted to *E. grandis* (Almeida et al. 2007). These contrasting results highlight the limitations of empirical water balance studies; plantation water use is situation specific and it is not possible to draw general conclusions about plantations being a positive, neutral or negative influence on water resources. Predicting the water balance of a new plantation in a new situation requires an understanding of the effect of plantations on the fluxes and storage in the stand and catchment.

As noted above, debate on the effect of plantations on water resources is neither new nor unique to South-East Asia and has accompanied the establishment of *Eucalyptus* species throughout the world and particularly in Australia (Greenwood 2013) and South Africa (Dye 2013). Markets for carbon create additional impetus for planting and have therefore intensified concerns (Jackson et al. 2005). In temperate regions, climate drying and increased variability in rainfall within and between years has increased pressure on water resources and therefore on plantation growers to account for their water use (Rangan et al. 2010). This has resulted in a large body of research that quantifies water use by plantations and the effect of plantation management on this usage (see reviews by (Whitehead and Beadle 2004; Brown et al. 2005; Farley et al. 2005; Dye and Versfeld 2007; van Dijk and Keenan 2007). These studies have provided a good understanding of the mechanisms by which plantations affect stream flow.

Although plantation water use is situation specific, there are well established, widely applicable physical principles that can support understanding, decision making and policy development, even in the absence of local data. These principles, developed mostly in temperate forests, are presented here and then tested using published and unpublished data (measured at the forest farm shown in Figure 1) from *Eucalyptus* plantations in South-East Asia. A simple tool is developed and used to estimate water use of *Eucalyptus* plantations in the major plantation regions of southern China, Indonesia, Thailand, Laos and Vietnam.

Plantation water use alone is insufficient for making balanced decisions about land and water allocation. The productivity and value of plantations and alternative land uses should also be taken into account. There is evidence of a positive correlation between plantation water productivity (*PWP*, the ratio of wood production to water use) and stand water use (White et al. 2009a; White et al. 2014). This creates an opportunity for plantation growers and water planners to manage the trade-off between productivity and water use at stand and catchment scale. This opportunity is discussed in the context of *Eucalyptus* plantations in South-East Asia.

Figure 1. A plantation of *E. urophylla* × *grandis* at Qipo Forest Farm near Nanning, Guangxi Province, China

This report is divided into the following sections:

Section 1 introduces general principles of plantation water use, provides definitions of key variables and a framework for quantifying the relationship between water use, the components of water use and production.

Section 2 explores the limits to plantation water use imposed by climate and quantifies the potential water use by different vegetation types within these limits.

Section 3 considers approaches for estimating water use by tropical plantations and tests a simple tool that predicts the crop factor (ratio of plantation water use to reference evaporation) as a function of plant-available soil water. This analysis suggests that the relationship between evapotranspiration and soil water content is similar for tropical and temperate *Eucalyptus* plantations. Some published values for growing season and dry-season evapotranspiration of rubber, cassava, paddy rice, hill rice, sugarcane and maize are also compared with *Eucalyptus* plantations.

Section 4 estimates plantation water use for the major plantation growing areas in Laos, Thailand, Vietnam, Indonesia and southern China. The results are summarised by climate type rather than by country. Climate is the main driver of evapotranspiration and a number of climate types can exist within a single country.

Section 5 explores some current plantation management practices in South-East Asia and their effect on water use by plantations.

Section 6 considers the water productivity of *Eucalyptus* plantations and the potential for improving growth and water productivity by adopting sustainable plantation practices, particularly in drainage lines, wetlands and in riparian zones.

Section 7 provides concluding statements and recommendations.

1 Important concepts and definitions

1.1 Plantation water use

For a *Eucalyptus* plantation, total water use or evapotranspiration (E_t) includes transpiration by crop trees (T_{TREE}), soil evaporation (S), canopy interception (I) and understorey transpiration (T_{WEED}) (Equation 1). Evapotranspiration by any land use may be similarly defined as the sum of all sources of evaporation from the land surface. Transpiration is the evaporation, through the leaf surface, of water that has been taken up from the soil by roots and transported to the leaves via stem and branches. Canopy interception is the evaporation of rainfall that is caught in the canopy of either the crop trees or weeds and does not reach the ground. Soil evaporation is the loss of water by evaporation directly from the soil surface.

$$E_t = T_{TREE} + I + S + T_{WEED} \qquad \text{Equation 1}$$

Many published reports of 'plantation water use' only include transpiration and do not account for other fluxes which can make up more than 50% of total evapotranspiration. All of the components of plantation evapotranspiration are amenable to management and tend to be complementary. For example, thinning may reduce transpiration and interception but will also increase soil evaporation and understorey or weed transpiration. Incomplete water balances should not be used to quantify or compare the effects of alternative land uses on water resources.

1.2 Potential evaporation

Potential or reference evaporation (E_0) is a measure of the potential or maximum energy-limited rate of evaporation. A useful, albeit imperfect, way of thinking about reference evaporation is as the rate of evaporation from a free water surface under a given set of conditions. Potential evaporation is mostly determined by radiation but it is also influenced by wind speed and humidity. These fundamental relationships are described by the Penman equation (Penman 1949). This equation was later modified to include the resistance to evaporation by vegetation in the Penman-Monteith equation (Monteith 1965). This latter model is used to calculate water use by vegetation in many of the most widely used models of plantation productivity and water use (e.g. Landsberg and Waring 1997; Battaglia et al. 2004).

There are many measures of potential evaporation but only two are used in this report. They have been selected because they are freely available or easy to calculate with readily available climate data. The FAO-56 reference evaporation (Allen et al. 1998) is calculated using the Penman-Monteith equation for 0.12 m tall grass with a constant conductance and albedo (reflectance). For forests and plantations, potential evaporation is more closely approximated by Priestley-Taylor potential evaporation (Priestley and Taylor 1972) which is on average about 1.26 times FAO-56. FAO-56 is freely available via FAO LocClim which can be downloaded from the FAO website (Grieser 2006). Priestley-Taylor potential evaporation can be calculated using Equation 2 where R_n is net radiation (about 70% of total solar radiation; Alados et al. 2003), s is the slope of the relationship between saturated vapor pressure and temperature, and γ is the psychrometric constant.

$$E_0 = 1.26 \left(\frac{s}{s + \gamma} \right) R_n \qquad \text{Equation 2}$$

1.3 The crop factor and climate wetness index

Potential evaporation is a useful concept in the consideration of water use by different vegetation types. It provides a reference against which to compare data from the same or different locations. The ratio of evapotranspiration (E_t) to reference evaporation is called the crop factor (k; Equation 3) and will be used here as the basis for comparing plantations with other land uses.

$$k = \frac{E_t}{E_0} \qquad \text{Equation 3}$$

Rainfall (P) and potential evaporation (E_0) both affect the water use of vegetation (see next section for details). Their combined effects are integrated in the climate wetness index (CWI; Equation 4), which is the ratio of rainfall to potential evaporation.

$$CWI = \frac{P}{E_0} \qquad \text{Equation 4}$$

1.4 What role do *Eucalyptus* trees play in the movement of water in the soil-plant-atmosphere continuum: are they pumps?

In the popular media and even in the scientific literature, trees (e.g. rubber, Tan et al. 2011), including eucalypts, are referred to as 'pumps' or even more colourfully as 'pumping machines'. This is not an accurate description of the role that trees, or any other type of plant, play in the movement of water in the soil-plant-atmosphere continuum. Use of the word 'pump' to describe eucalypt trees suggests that they generate the force that moves water from the soil to the atmosphere. This energy is actually provided by solar radiation, which generates temperature and pressure gradients between the air surrounding a tree and the moist air inside the trees, other plants in the forest and the soil matrix. In the literature that describes evaporation from the environment, the movement of water in the soil-plant-atmosphere continuum is often described using an electrical analogy. In this analogy, eucalypt trees and all other plants act as variable resistors between the wet soil and the drier atmosphere. The resistance of *Eucalyptus* canopies decreases as a function of leaf area index and is also affected by the aperture and number of small pores in the leaf surface called stomata. There is a vast literature describing the response of these pores and of leaf area index to the environment. Eucalypts, like all other plant species, vary leaf area and stomatal resistance to maximise carbon gain per unit of water used. This is a universal behavior which all plants share.

The word 'pump' is an emotive way of describing a tree that is not an accurate description of the role trees plays in the water cycle. Trees are variable resistors. Other surfaces in the environment also act as resistors in the system, including the soil matrix, surface rocks, the litter layer, fungi and weeds.

1.5 Water security

Sustaining a secure water supply for communities is a complex allocation problem with biophysical and social dimensions. The allocable pool of water is usually defined as stream flow under a reference land use less an allocation for environmental flow and an allowance for inter-annual variation. Changes in land use affect stream flow via changes in evapotranspiration. Addressing the effect of plantations on water security is an issue to be considered by those responsible for local natural resource management. This report aims to provide information and tools to facilitate the consideration of *Eucalyptus* plantations in this process.

Section 1 summary: Important concepts and definitions

- Plantation water use (evapotranspiration) is the sum of transpiration by the trees, soil evaporation, canopy interception, and understorey and weed transpiration. Studies where all four fluxes are measured are very rare. Most studies that are purportedly about plantation water use are in fact studies of crop tree transpiration.
- To develop strategies to manage plantation water use and plantation water productivity, experiments and monitoring programs must provide information about all of the components of evapotranspiration.
- Management affects all of the components of evapotranspiration.
- The word 'pump' is an emotive way of describing a tree that is not an accurate description of the role trees plays in the water cycle. They are not pumps. They more closely approximate variable resistors between the moist soil and the dry atmosphere.
- Incomplete water balances should not be used to compare the effects of alternative land uses on water resources.

2 Water and energy limits to plantation water use

2.1 Applying general principles to South-East Asia

In order of decreasing influence, the factors affecting evaporation from the land are: rainfall (water limit); potential evaporation (energy limit, defined in Section 1); topography and geology (storage); and vegetation (resistance). Although vegetation cover is a secondary determinant of evapotranspiration, it can be have an important effect on water availability if stream flow is a small proportion of rainfall. This section explores the limits to water use by plantations and identifies situations in South-East Asia where planting *Eucalyptus* might have an effect on catchment water balance and warrant further analysis.

At any given time, water use by plantations and alternative land uses is either water or energy limited. When rainfall is less than potential evaporation, water use by a plantation is limited by rainfall (water limited) (Budyko 1974; Figure 2a). When potential evaporation is less than rainfall, then the water use of a plantation is limited by available energy (Budyko 1974; Figure 2a). Over long time periods, assuming there is no change in catchment storage, the Budyko (1974) framework can be used to partition rainfall into evapotranspiration and run-off. This framework uses the relationship between the ratio of evapotranspiration to potential evaporation (the crop factor; Equation 3) and the ratio of rainfall to potential evaporation (the climate wetness index; Equation 4). Run-off is simply the difference between the crop factor (k) and climate wetness index (CWI) multiplied by potential evaporation (E_0) (Equation 5).

$$\text{Run-off} = (CWI - k)E_0 \qquad \text{Equation 5}$$

This Budyko framework has been adapted to account for the effects of catchment characteristics, including vegetation cover, on evaporation (Fu 1981; Zhang et al. 2001; Zhang et al. 2004; Donohue et al. 2007; Donohue et al. 2009; Teng et al. 2012; Zhang and Chiew 2012). Zhang et al (2004) analysed a global data set and fitted relationships between the crop factor and climate wetness index for plantations, natural forest and grassed catchments. These relationships expressed the crop factor (k) as a function of the climate wetness index (CWI) and an empirical catchment characteristic parameter (c) that integrated the effects of vegetation type, storage (depth × texture) and topography on evapotranspiration (Equation 6).

$$k = 1 + CWI + \left(1 + [CWI]^c\right)^{\frac{1}{c}} \qquad \text{Equation 6}$$

A catchment characteristic parameter (c) of 4, 3 and 2.55 provided the best fit respectively with observations for plantations, natural forests and grasses. The resultant curves for plantation, natural forest and grass are shown in Figure 2a with the water and energy limits described by Budyko (1974). Using these curves, evapotranspiration was calculated for plantations, natural forest and annual pasture for a range of climate wetness indices, assuming a constant potential reference evaporation of 1500 mm (Table 1 and Figure 2b). Two cases are shaded in Table 1 that serve to illustrate the utility of the climate wetness index as a criteria for identifying areas where plantation establishment may have an important effect on run-off. They also highlight the danger of using absolute differences in evapotranspiration to make land-use decisions.

Case 1: Climate wetness index 0.5, potential evaporation 1500 mm

For this case, predicted annual evapotranspiration by a plantation was 727 mm and run-off was 23 mm. For the same climatic conditions, predicted evapotranspiration and run-off from a natural forest were 690 mm and 60 mm. The model predicts that clearing all of a native forest catchment and planting *Eucalyptus* in plantations would increase predicted evapotranspiration by 37 mm or 60% (Table 1). In this very water-limited situation, the absolute increase in evapotranspiration predicted is small but the proportional reduction in stream flow is predicted to be large.

Case 2: Climate wetness index 1.5, potential evaporation 1500 mm

The predicted run-off from plantation and native forest was 853 mm and 953 mm respectively. The absolute difference is larger (100 mm) but the proportional reduction in run-off is much smaller. Importantly, predicted run-off from both land uses is very large (Table 1).

Zhang et al. (2004) noted that the crop factor is not very sensitive to either vegetation or catchment characteristics when rainfall is less than half of potential evaporation, and that water was not scarce when the climate wetness index exceeded 1.5. While the second observation is sound, the small differences in evapotranspiration between plantations and native forests that are predicted for a climate wetness index of 0.5 will result in a large proportional reduction in stream flow (Table 1). This may be important in some circumstances.

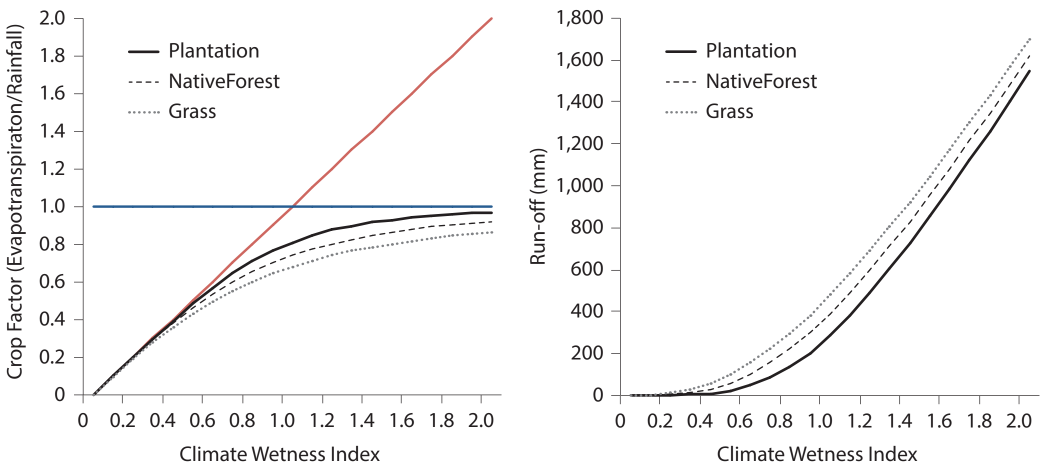


Figure 2. a) The relationship between the crop factor (*k*: the ratio of evapotranspiration to potential evaporation—Equation 2) and the climate wetness index (CWI: the ratio of rainfall to potential evaporation—Equation 3) showing the energy and water limits to evapotranspiration. The curved lines are potential evaporation lines from Zhang et al (2004) for different values of the catchment parameter (w: given values of 4 for plantation; 3 for natural forest; 2.5 for grass by (Zhang et al. 2004). b) The relationship between run-off and the climate wetness index assuming potential evaporation of 1500 mm.

Table 1. Average annual evapotranspiration and run-off estimated for plantation, native forest and grass using the model of Zhang et al (2004) (Equation 6) for a hypothetical location with annual potential evaporation of 1500 mm and for a range of annual rainfall from 750 mm to 3,000 mm.

CWI	Rain	Plantation		Native forest		Annual grass	
	mm	E_t (mm)	Run-off (mm)	E_t (mm)	Run-off (mm)	E_t (mm)	Run-off (mm)
0.5	750	727	23	690	60	649	101
0.7	1050	967	83	895	155	829	221
1.0	1500	1216	284	1110	390	1020	479
1.3	1950	1348	602	1240	710	1145	805
1.5	2250	1396	853	1297	953	1203	1046
2	3000	1454	1545	1380	1620	1298	1701

The crop factor, evapotranspiration and run-off are most sensitive to vegetation cover for a climate wetness index of 1. Sensitivity decreases steeply for values of the climate wetness index below one but the catchment water balance is relatively sensitive to vegetation cover when the climate wetness index is in the range 0.7 to 1.3 (Figure 3).

Estimates of average rainfall and potential evaporation can be obtained from FAO's LocClim (Grieser 2006). Figure 4 is a map showing average annual climate wetness index (CWI) throughout South-East Asia. When the CWI is greater than 1.5, water is not scarce and annual run-off from all vegetation types will be large (Table 1). This applies in much of Sumatra, Kalimantan, Java, Malaysia, the Philippines, East Timor and northern Vietnam, and to parts of southern China. When the CWI is less than 0.5, water is scarce but evapotranspiration is not sensitive to vegetation cover. However in these situations, very small changes in evapotranspiration will have a large proportional effect on run-off. This applies to large parts of southern India (not shown), a region in which there has been a great deal of controversy about the potential impacts of *Eucalyptus* plantations on water resources.

Evapotranspiration is most sensitive to vegetation cover and management when the climate wetness index is in the range 0.7 to 1.3. This applies to central Vietnam, much of Thailand, parts of Cambodia, Laos and Myanmar, and Guangxi and southern Guangdong provinces in China. The authors of this report did not visit Cambodia or Myanmar as part of this study and the focus is therefore on China, Thailand, Laos and central Vietnam.

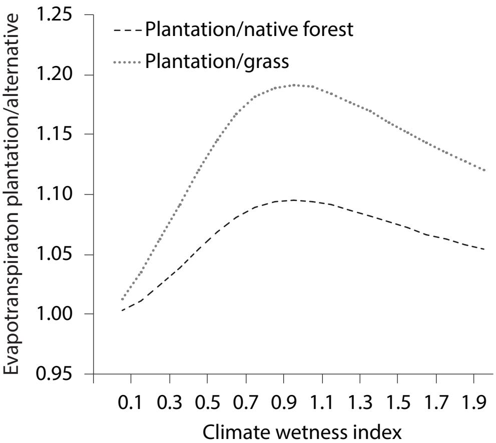


Figure 3. The ratio of evapotranspiration by plantations to evapotranspiration by grass and natural forest calculated using Equation 6 (Zhang et al. 2004). Evapotranspiration is most sensitive to vegetation cover for a climate wetness index of 1. Sensitivity decreases steeply for values of the crop factor below 1. When the climate wetness index is less than 0.5, rainfall imposes an absolute limit on water use for all vegetation types (see also Figure 2). When the climate wetness index is greater than 1.5, water is not scarce and run-off is large for all vegetation types (Table 1).

2.2 Partial planting of catchments

The differences between vegetation types that are predicted using the model of Zhang et al. (2004) are based on analysis of large global data sets that only include catchments where more than 80% of the land is covered by a given vegetation type. In most parts of South-East Asia, this is not the case and catchments are a mosaic of land uses. In an analysis of catchments with multiple land uses, Zhang and Chiew (2012) found that using an area-weighted average of water use, estimated for different land uses, gave an unbiased prediction of stream flow and evapotranspiration for the set of catchments. This is a reasonable approach for large-scale water planning, particularly in areas where data on vegetation characteristics and local hydrogeology is limited (Zhang and Chiew 2012).

In small tertiary or quaternary catchments in upland areas of Vietnam, Thailand and Laos, the location of plantations will be an important determinant of productivity and therefore of water use. In a modeling analysis of the impact of plantations on stream flow in a catchment in central Victoria, Australia, Gilfedder et al. (2010) predicted that planting areas with concave slope and riparian zones had a greater impact on stream flow than planting in other parts of the catchment. It is worth noting that plantation water productivity is positively correlated with water use, and Gilfedder et al. (2010) also predicted that plantation water productivity was greatest in those areas where plantation establishment had the greatest impact on stream flow (see Section 6 for a detailed consideration of the implications of this observation). Many forest practices codes around the world preclude forestry operations in riparian zones; plantation establishment and harvesting are not usually practiced in parts of catchments where plantations are known to have the greatest impact on stream flow. This precludes plantation forestry in locations where conversion of water to wood is likely to be most efficient (see Section 6).

2.2 Groundwater use by plantations: an application of energy and water limits

The analysis presented in Section 2.1 applies to rainfall-dependent plantations or plantations that do not have access to water other than rainfall. Some plantations are established in areas where their roots can access unconfined aquifers or groundwater (Benyon et al. 2006). O'Grady et al. (2011) analysed published data for plantations and natural forests with access to groundwater and showed that measured water use exceeded rainfall (the water limit; Figure 2) by an amount equivalent to the net groundwater use of the forest. Thus, an understanding of the limits to water use can be used to identify plantations with access to additional sources of water.

If minimising water use by plantations were the only goal of plantation design, then the observation that plantations of *Eucalyptus* can use groundwater would lead us to avoid areas with unconfined aquifers. This simple one-criterion approach may in some circumstances result in the unintended consequence of increased water use by wood production systems

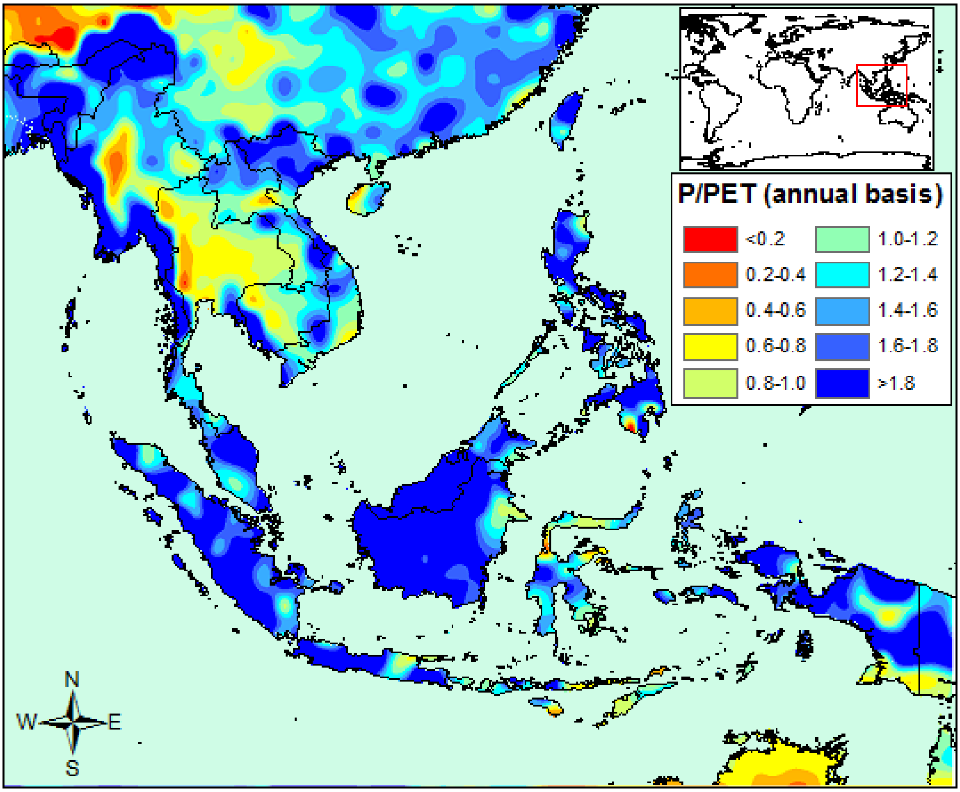


Figure 4. A map of South-East Asia showing the climate wetness index (CWI: ratio of rainfall to potential evaporation; P/PET). Evapotranspiration is relatively insensitive to vegetation cover when the CWI is less than 0.5. When the climate wetness index is greater than 1.5, water is not scarce. Areas in South-East Asia where water can be scarce in the dry season and evapotranspiration is sensitive to vegetation cover are shaded, including central Vietnam and much of Thailand.

at larger scales. This is because wood production per unit water use is positively correlated with plantation water use (Stape et al. 2004, 2008; White et al. 2014) so that plantations established with access to groundwater resources may be more water-use efficient production systems than plantations without access to groundwater. Careful multi-factor optimisation might still indicate that avoiding wet areas is the best option, but it might also lead to the counter-intuitive conclusion that planting some areas with shallow groundwater resources is the best way of managing the wood-water trade-off at the catchment scale. The concepts of water-use efficiency are developed more fully in Section 6 but underpin the notion that maximising productivity and water use per hectare planted may be the best route to optimising the value of landscapes that include plantations.

2.3 Variation in water use within the rotation

In South-East Asia, *Eucalyptus* plantations are managed on a rotation of between six and 12 years, and the trend is towards decreasing rotation lengths. In the media, the reduction of rotation lengths is often said to be associated with increased water use (Harwood and Nambiar 2014). Water use by *Eucalyptus* plantations will decrease after harvest and replanting to a rate similar to an annual pasture (e.g. Worledge et al. 1998) and then increase before reaching a steady state soon after canopy closure. To allow for the distribution of plantation age in the South Australian water allocation policy, the average value of the crop factor is assumed to be 0.8 of the maximum. A trend towards more frequent harvesting will reduce the proportion of time when plantations are at post-canopy closure and may reduce average annual water use of the system. This is contrary to popular expectations that shortening rotation length will increase water use because water use is correlated with productivity.

2.4 Water use, productivity and leaf area index

The popular assumption that shorter rotations will be associated with increased water use may not be true. This assumption arises from an overly simplistic view of the relationship between productivity and water use, and an over emphasis on transpiration in discussions about the relationship between productivity and water use. Relationships among the components of evapotranspiration and the production of both dry matter and wood are considered in detail in Section 6.

As part of this section on the water and energy limits to evapotranspiration, two main points are made. Firstly, plantation productivity varies through time and there are three distinct phases: an initial slow phase; a second rapid growth phase; and a third phase where productivity plateaus. Together, these three phases make up the classic sigmoidal growth curve. Total water use by a plantation will be similar in the rapid growth and plateau phases and less in the initial slow growth phase. Shortening rotations may in fact increase the proportional importance of this slower phase to the rotation water balance.

Secondly, productivity is linearly related to light interception and non-linearly related to leaf area index (*LAI*). This is due the self-shading effect associated with increases in leaf area index. The relationship between leaf area index and light interception has a steep initial slope that decreases continually towards an asymptote of complete interception. This characteristic relationship has a number of important consequences, but the most important here is a non-linear relationship between leaf area index and water use. Up to a leaf area index of three, the relationship is close to linear but further increases in leaf area index have progressively less impact on total water use.

2.5 Low- or dry-season flow

Variations on the Budyko (1974) model, such as proposed by Zhang et al. (2004), can be used to estimate annual evapotranspiration and to distinguish between broad vegetation types. For water planning at the catchment or larger scales, this will usually be sufficient. In data-poor regions, this may be an appropriate first step. However, conflict between plantations and alternative water uses often occurs during the dry season and at very local scales. New plantations are often established in situations where there is limited soils data and where the physiological responses of target species to climate and management are not well described. Large-scale planting of *Acacia* and *Eucalyptus* plantations in South-East Asia, for example, is a relatively new phenomenon and very few direct measurements of water use have been made in these plantations. Although a lot of this planting has occurred in tropical environments with climate wetness indices approaching or exceeding

1.5, these climates are often seasonally dry and there is very little capacity for water storage. Under these circumstances, dry-season water use by plantations may have an important effect on low flows.

Farley et al. (2005) evaluated 504 observations from 26 sites in mainly temperate environments and found that low-flow effects were equally, if not more, important than the influence of vegetation on annual water yield, "possibly leading to shifts from perennial to intermittent flow regimes in dry-region streams". *Eucalyptus* showed a larger effect on low flow than *Pinus* due to the stronger dry-season regulation of water use by pine compared to eucalypt plantations (Lima et al. 1990; Myers and Talsma 1992; Bren 1993; Castelao et al. 1996). Many afforestation studies have documented significant reduction or cessation of flow, but there are challenges with measuring and understanding low-flow conditions. Bruijnzeel et al. (2004) calls this "the single most important 'watershed' issue requiring further research". Low-flow impacts will be local rather than regional; large streams are more likely to be perennial (Vertessy et al. 2003). Stream flow becomes erratic under drier conditions, and this variability obscures controls on low-flow hydrology (Vertessy et al. 2001) and extrapolation from short-term studies is even more difficult under changing rainfall patterns seen around the globe.

Brown et al. (2005) analysed data from the Bosch and Hewlett (1982) studies and an additional 72 experiments to examine flow duration relationships, and Lane et al. (2005) used data from 10 Southern Hemisphere experiments to develop a model to predict the impact of afforestation on flow duration, including estimations of zero flow days. Brown et al. (2013) defined three classes of changes in stream flow duration: those with an increase in dry days; those with larger reductions in low flow than high flow; and those with uniform response. Smakhtin (2001) reviewed low-flow measures and indices to evaluate anthropogenic change and found that afforestation has the potential to increase the number of low- or zero- flow days in seasonally dry catchments. Andreassian (2004) concluded, in a review of the impacts of afforestation on low flow, that except in extreme drought years, the impact of afforestation on low flow was slight. It cannot be concluded from this that plantations do not have important local effects; the impact of afforestation on flow was similar in magnitude to that attributed to measurement uncertainty.

Until there have been definitive studies into the effects of plantations on low flow in South-East Asia, it would be wise to avoid planting large proportions of small, upland catchments where people are dependent on dry-season stream flow for water.

Section 2 summary: Climatic limits to plantation water use

- Vegetation cover is a secondary determinant (after rainfall, available energy and hydrogeology) of evaporation from land.
- Vegetation cover can have important impacts on annual stream flow where stream flow is a small percentage of rainfall.
- The absolute limits to water use by vegetation are determined by available water and energy.
- Analysis of global data sets has shown that, on average, plantations use slightly more water than natural forest, which in turn uses more water than annual crops and pastures.
- When the climate wetness index is greater than 1.5, water is not scarce; this applies throughout Sumatra, western Java, Kalimantan, Malaysia, northern Laos and Vietnam, and parts of southern China.
- Stream flow is most affected by plantation establishment when the climate wetness index is between 0.7 and 1.3. This applies in much of Thailand, central Vietnam and Laos, and in some regions in Cambodia and Myanmar.
- The maximum proportional increase in evapotranspiration due to plantation establishment occurs when average annual rainfall is equal to reference evaporation.
- The water use and water-use efficiency of plantations will be greatest in wet areas of catchments, such as the break of slope, stream-side reserves and areas where groundwater is accessible (see Section 6 for a detailed treatment of the implications of this observation).
- The effects of plantations on dry-season flow are poorly understood. Published reviews suggest that *Eucalyptus* plantations will cause a larger proportional reduction in dry-season flow than alternative plantation species (e.g. pines) that exhibit stronger stomatal regulation of transpiration during dry periods.
- Until there have been definitive studies of the effects of plantations on low flow in South-East Asia, it would be wise to avoid planting large areas of small, upland catchments where people are dependent on dry-season stream flow for water.

3 Seasonal variation in water use by plantations of *Eucalyptus* and alternative crops

In much of Thailand, central Vietnam and southern Laos, the climate wetness index is in the range for which annual evapotranspiration is relatively sensitive to vegetation cover (Figures 3 and 4). In these areas, there is pronounced seasonal variation in rainfall and a dry season that can last for several months. The effect of *Eucalyptus* plantations on water resources will therefore depend on seasonal variation in evapotranspiration, rainfall and run-off. This section develops a simple approach to estimate water use by tropical *Eucalyptus* plantations for all months of the year.

3.1 Process-based models

Process-based models predict growth and water use of plantations by representing the fundamental physiological responses of trees to their environment. This approach should mean process-based models require less calibration for local conditions than empirical models. The most widely applied process-based models of plantation growth and water use are 3PG (Physiological Principles of Plantation Growth, Landsberg and Waring 1997) and CABALA (CArbon BAlance and ALlocation, Battaglia et al. 2004).

The plantation growth model 3PG has been parameterised for tropical plantation species (Almeida et al. 2004) and used to model evapotranspiration by *E. urophylla* and eucalypt hybrids in Brazil (Almeida et al. 2007). CABALA, which models the carbon and water balance of plantation forests, has also been parameterised for *E. grandis* and tropical *Acacia*s, and could be used to model the effect of silvicultural interventions such as thinning and pruning on stand-scale water balance. The application of either model requires detailed information about soil depth and soil physical and chemical characteristics. This kind of data is either absent in South-East Asian plantation inventory or is available for very few sites. The 3PG model requires extensive calibration using local growth and allometric data (Almeida et al. 2004). CABALA can only be applied with confidence after an intensive research program to parameterise the model for tropical soils and for tropical plantation species. Both models can however provide general principles about the relationship between species attributes, management practices and water use.

Controversy about water use by plantations often occurs during the initial expansion phase of a new plantation enterprise, when local data for calibration is unavailable. Further, the extension of knowledge can be more readily transferred with simple relationships that are easily understood and readily traced back to the source experiments. Thus, a more general and simpler approach than process-based models is needed for modeling seasonal patterns of water use by tropical *Eucalyptus* plantations.

3.2 Vegetation characteristics for temperate *Eucalyptus* plantations

One approach to modeling seasonal variation in water use and quantifying the difference between plantations and other land uses is to use 'vegetation characteristics' such as those described by White et al. (2001) for a range of planted forests. Vegetation characteristics are a relationship between the crop factor (*k:* the ratio of actual to potential water use) and relative plant-available soil water[1]. The crop

[1] Relative plant-available soil water is the ratio of the current amount of water stored within the root zone to the maximum amount of plant-available water that can be stored in the same soil volume. While the functions may be similar for plantation and grass, these vegetation types will differ in the volume of soil from which they can extract water.

factor integrates the effect of soil and atmospheric drought on transpiration, interception and soil evaporation through changes in leaf area and canopy conductance. There is enough information in the literature to construct robust vegetation characteristics for the major temperate plantation species and there are defensible models for tropical plantation eucalypts.

In Tasmania and Western Australia, substantial long-term measurements of water balance and soil water content have been collected from *E. globulus* and *E. nitens* (White et al. 1994a,b, 1996 2009b, 2010). Battaglia and Sands (1997) developed a 'vegetation characteristic' for *E. globulus* by fitting a sigmoidal function to data from irrigated and rain-fed plots in Tasmania (see Honeysett et al. 1996 for details). This model (Equation 7) describes the relationship between the crop factor (k) and relative plant-available soil water content (w), where w_0 is the soil water content for which the crop factor (k) is 0.5 and a_w is the slope of the linear portion of the curve. The vegetation characteristic for *E. globulus* plantations and the data from which it is derived are shown in Figure 5.

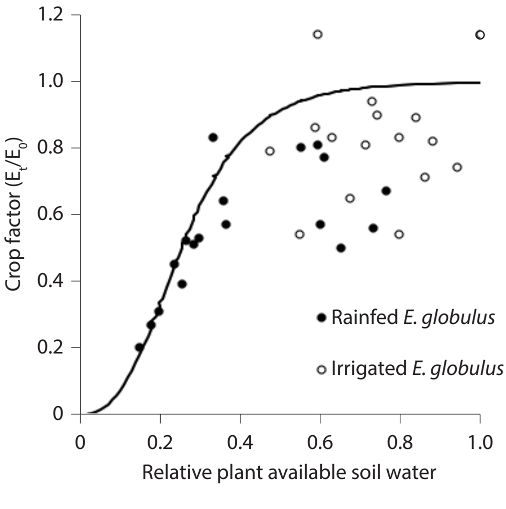


Figure 5. The relationship between the crop factor (***k***) and relative plant-available soil water for irrigated and rain-fed *E. globulus* in Tasmania, Australia. The line is the function used in ProMod by Battaglia and Sands (1997); Equation 7.

$$k = \frac{w^2 e^{a_w w}}{w_0 e^{a_w w_0} + w^2 e^{a_w w}} \quad \text{Equation 7}$$

The model developed by Battaglia and Sands (1997) predicts that under well-watered conditions, evapotranspiration of *E. globulus* is similar to potential evaporation (a crop factor of nearly one). Field data from the Biology of Forest Growth experiments (Myers and Talsma 1992; Raison and Myers 1992), an effluent irrigated plantation (Myers et al. 1998) and a series of plantations in southern Australia (Benyon et al. 2006) suggest a similar maximum value of the crop factor for *Pinus radiata*. The maximum crop factor observed in an *E. urophylla* plantation in southern China was also approximately one (Lane et al. 2004).

The crop factor in *E. globulus* plantations decreases very slowly under moderate soil water deficit until a threshold soil water content or tipping point is reached, beyond which the trees begin to exert very tight control over plantation water use (Figure 5). In water-limited plantations, there is a very tight relationship between the crop factor and relative plant-available soil water (Battaglia and Sands 1997).

3.3 A vegetation characteristic for tropical *Eucalyptus* plantations

There is only one published study where all of the components of evapotranspiration were measured in a tropical *Eucalyptus* plantation (Lane et al. 2004), although partial water balances, in which some components have been estimated, are available from other studies (Almeida et al. 2007; Hubbard et al. 2010; Stape et al. 2004, 2008). The maximum crop factor observed by Lane et al (2004) was approximately one and the threshold water content or tipping point for regulation of evapotranspiration was about 0.5. These values are very similar to those reported by Battaglia and Sands (1997) for *E. globulus*. These limited published studies suggest that the 'vegetation characteristics' of temperate and tropical *Eucalyptus* plantations may be quite similar. Perhaps this is not surprising since the major *Eucalyptus* plantation species belong to the same sub-genus (Symphyomyrtus) and all grow naturally on relatively mesic sites.

The Guangxi Forestry Research Institute has collected more than a year of data in an *E. urophylla* × *grandis* plantation at Qipo Forest Farm, south of Nanning, China. This data was used to make monthly estimates of relative plant-available soil water, rainfall, potential evaporation, transpiration, interception and soil evaporation, and understorey transpiration from July 2013 to June 2014. Details of the methods used and calculations made to estimate each component are provided in Appendix 1. For the measurement year, transpiration by the crop trees was 349 mm, interception was 260 mm and understorey water use was estimated to be 303 mm. Adding these gives a total evapotranspiration of 912 mm for the period compared to rainfall of 1260 mm.

In the *E. urophylla* × *grandis* at Qipo Forest Farm, the ratio of evapotranspiration to potential evaporation (the crop factor: *k*) decreased during periods with very little rain in September 2013, January 2014 and again at the end of the dry season in May and June of 2014. Together, soil evaporation and understorey transpiration were approximately one-third of evapotranspiration. This observation is discussed in more detail in the next section. Although there is no data available for *E. urophylla* × *grandis* under severe water stress, the available data are consistent with the hypothesis that the crop factor in tropical *E. urophylla* × *grandis* plantations responds to soil water deficit in the same way as previously observed in a temperate *E. globulus* (z 6). These data were collected at the site shown in Figure 7.

3.4 A water-use tool for tropical *Eucalyptus* plantations

The vegetation characteristic in Figure 6 was incorporated in a simple tool for estimating water use by fast-growing *Eucalyptus* plantations. The tool is described in Appendix 2. It calculates evapotranspiration for each month, as the product of the crop factor (calculated using Equation 7) and potential evaporation. The soil water deficit at the end the month is then calculated using a simple water balance, and this new water status is used to calculate plantation water use for the next month. This process is repeated each month for the entire year.

There are not enough published studies to conduct a rigorous test of the model, but for studies in China (Lane et al. 2004) and Brazil (Almeida et al. 2007) it predicts annual potential evapotranspiration to within 50 mm of the published values. The only input data required are monthly rainfall and potential evaporation, soil depth and texture. An estimate of soil stone or rock fraction can also be provided if it is known.

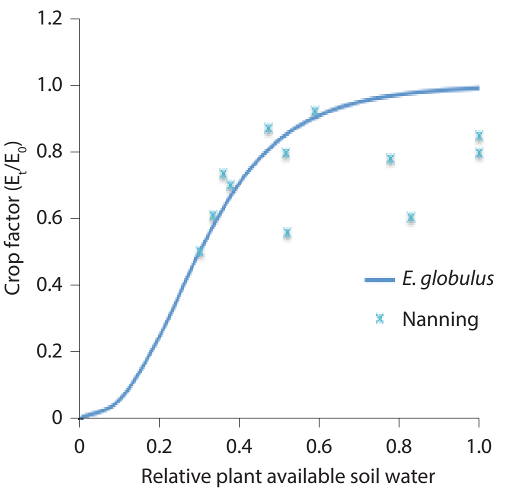


Figure 6. The relationship between the crop factor (*k*) and relative plant-available soil water for *E. urophylla* × *grandis* plantations at Qipo Forest Farm near Nanning in Guangxi Province, China. The line is the functions used in ProMod by Battaglia and Sands (1997).

Figure 7. Instruments for measuring net water and carbon flux are mounted on this tower at Qipo Forest Farm near Nanning, Guangxi Province, China.

In Section 4, this tool is used to quantify average plantation water use for the major plantation regions in South-East Asia. These analyses are coupled with information about the plantation industry and current management practices to make an assessment of the likely impact of plantation water use.

3.5 Cassava, paddy and hill rice, sugarcane, and shifting cultivation

An important step for quantifying the change in evapotranspiration and stream flow due to afforestation is to quantify water use by alternative land uses. Water use by plantations must be compared to the previous land use and to alternative new uses of the land. In those parts of South-East Asia that have a climate wetness index between 0.7 and 1.3, including central and northern Thailand, much of Laos and central Vietnam, the main crops are paddy rice, hill rice, cassava and sugarcane. Shifting cultivation is also practiced on substantial areas of Laos that are currently designated as forested.

Paddy rice

There are a number of studies that have quantified the growing or wet-season crop coefficient of rice. In an early review, Tomar and O'Toole (1980) found that the average wet-season crop factor for paddy rice in South-East Asia was about 1.2 (the reference evaporation used was similar to FAO-56). Published values of the growing-season crop coefficient of paddy rice are consistently greater than 1.1. During the growing season, paddy rice is inundated and the duration of inundation determines the length of the growing season. The control of inundation varies markedly throughout South-East Asia and this has an effect on both productivity and water use. In northern and central Thailand, the growing season for rice extends from May to late November or early December, and inundation is fairly well maintained for the entire period. In contrast, irrigation in Laos is much less controlled and areas described as irrigated vary from some that are inundated for the growing season to others with uncontrolled flooding (Rebelo et al. 2014). While there is a reasonable understanding of growing-season water use in paddy rice, there is very little data available on evapotranspiration during the dry season.

Sugarcane and cassava

There are fewer published studies for sugarcane and cassava in South-East Asia than for paddy rice. One study in northern Thailand reported maximum values for the crop factor of 1.1 for sugarcane and 1.2 for both cassava and maize (Watanabe et al. 2004). In all three crops, the crop factor was greater than 0.9 throughout a six-month growing season from May to November, and water use was about 1 mm per day during the dry season (Watanabe et al. 2004).

Comparing eucalypts with cassava and paddy rice: an example from Thailand

Table 1 gives values of annual evapotranspiration by *Eucalyptus* plantations, cassava and paddy rice for median rainfall. It was assumed that:

1. the *Eucalyptus* plantation was a block planting on a site where the soil was approximately 1.5 m deep with sand to a depth of 20 cm and clay loam below 20 cm
2. the paddy rice was irrigated and had a crop factor of one throughout a growing season that extended from May to the end of November
3. the cassava also had a crop factor of one during a growing season that was defined as the period for which monthly rainfall exceeded potential evaporation
4. the dry-season water use of cassava and paddy rice was the maximum of monthly rainfall and 30 mm a month (Watanabe et al. 2004).

In these three regions, predicted water use by *Eucalyptus* plantations was greater than for cassava and the ratio of *Eucalyptus* to cassava water use varied from 1.03 to 1.10 (Table 2). These values are consistent with the ratio between the relationships in Figure 3 but for both crops, the absolute values are lower than those predicted using the model of Zhang et al (2004) (Equation 5).

Table 2. Estimated average annual water use (mm) by *Eucalyptus*, cassava and paddy rice for three important plantation growing regions in Thailand.

	Region		
	Chachoengsao	Songkhla	Chiang Mai
Eucalyptus	1052	1097	902
Cassava	991	990	873
Paddy rice	1100	1004	958

Rubber and *Eucalyptus* plantations

Rubber plantations are an important alternative to *Eucalyptus* plantations throughout South-East Asia and southern China. In a comparison of the annual water use of rubber plantations and natural rainforest in south-western China, Tan et al. (2011) found that in a period with annual rainfall of approximately 1,530 mm, the evapotranspiration of rubber plantation was 1,130 mm. During the same period, average annual water use of rainforest was 940 mm.

Using the steady state model described by Equation 6 and climate data reported by Tan et al. (2011) the estimated evapotranspiration of *Eucalyptus* plantation and native forest are respectively 1,110 mm and 935 mm compared to the 1,110 mm observed in the rubber plantation. The Water-Use Tool developed using the Qipo data predicts that annual evapotranspiration of *Eucalyptus* would be 1,090 mm in the same location. There are no direct comparisons of rubber and *Eucalyptus* plantations in the literature but this analysis suggests that in south-western China, water use by these crops is very similar.

Eucalyptus and *Pinus* plantations

Again, there are few complete comparisons of *Eucalyptus* and *Pinus* plantations in similar locations. In a recent study in southern Australia, Benyon and Doody (2014) found that annual evapotranspiration of *Pinus radiata* and *E. globulus* plantations was not significantly different and this applied to plantations with and without access to groundwater. The contribution of the components of evapotranspiration differed between the two species, with soil evaporation being larger for *E. globulus* than *P. radiata* and canopy interception was greater for *P. radiata* than *E. globulus*. Again, this highlights the conservative, energy-dependent nature of evapotranspiration and the folly of comparisons between crops based on incomplete water balances.

Section 3 summary: Seasonal variation in water use by plantations of *Eucalyptus* and alternative crops

- The maximum crop factor for *Eucalyptus*, cassava, sugarcane, maize and paddy rice is greater than one. Evapotranspiration is approximately equal to potential evaporation throughout the growing season.
- Some evapotranspiration occurs during the dry season in *Eucalyptus* plantations but this has also been observed in cassava, maize and sugarcane.
- The vegetation characteristic of tropical *Eucalyptus* plantations is similar to that previously observed in *E. globulus* in temperate regions.
- Annual water use by rubber plantations is similar to that predicted for *Eucalyptus* plantations using the vegetation characteristic developed in this section.
- In southern Australia, annual evapotranspiration by *Pinus* and *Eucalyptus* plantations is very similar.

4 Water use by *Eucalyptus* plantations in South-East Asia

In Sumatra, Kalimantan, western Java, Malaysia, parts of Guangxi and Guangdong provinces in China, northern Vietnam, and some parts of eastern and northern Laos, rainfall is much greater than potential evaporation. *Eucalyptus* plantations will not have an important effect on annual evapotranspiration or stream flow in these regions (see Lane et al. (2004) for an example in Guangdong Province, China). In Thailand, central Vietnam, and in parts of Laos, Cambodia, Myanmar and southern Guangxi Province in China, the ratio of rainfall to potential evaporation is in the range 0.7 to 1.3, where Zhang et al. (2004) predict the maximum effect of vegetation cover on evapotranspiration (Figure 4).

4.1 Comparison of the water-use tool with a steady-state model

Most of South-East Asia, particularly those areas with a climate wetness index in the range 0.7 to 1.3 experience a pronounced dry season during which potential evaporation exceeds rainfall for several months (see Figure 8 for examples). This presents a challenge for using steady-state models based on annual climatic variables such as the curves shown in Figure 3 (Zhang et al. 2004). During the wet season, rainfall is much greater than potential evaporation, evapotranspiration will be energy limited and there is likely to be substantial stream flow. During the dry season, potential evaporation is much greater than rainfall and evapotranspiration is water limited. In locations such as Quy Nhon in central Vietnam, there is a very long dry season and plantations of *Eucalyptus* will regulate water use by closing stomata and shedding leaves. Both of these responses occur in tropical *Eucalyptus* plantations (Roberts and Rosier 1993). Under the circumstances that prevail in the drier parts of South-East Asia, a model that does not account for the seasonal variation in soil water content, and the resultant increase in canopy resistance, may overestimate evapotranspiration by plantations or alternative land uses.

Using the water-use tool developed in this project, evapotranspiration was calculated for each of 28 locations in South-East Asia and two each in Brazil and south India. It was assumed that the soil was 2 m deep with sand to 20 cm and clay below 20 cm. The annual crop factor calculated for each site is shown in Figure 9 with the curve for plantations from Zhang et al. (2004). The model of Zhang et al.(2004) describes the upper boundary of the crop factor, estimated using a vegetation characteristic, but overestimates the crop factor for many sites in Laos and Vietnam where annual rainfall is very seasonal (Figure 9). Both are modelled values, but only one model accounts for the effects on plantation water use of the seasonality of rainfall, evaporation and variation in plant-available soil water.

The difference between the crop factor predicted by Zhang et al. (2004) and the vegetation characteristic was plotted against the ratio of rainfall for the wettest four to the driest four months. The seasonality of rainfall correlated with the variation in the crop factor predicted using the two models (Figure 10).

For the plantation regions in central Vietnam and Laos, the crop factor estimated using the Zhang et al. (2004) model is much larger than the crop factor calculated using the tool developed in this project. The rainfall in these regions is very seasonal. Stream flow during the wet season is very large and plantations become water stressed in the dry season. For most other plantation regions, including south Sumatra, Guangdong and Guangxi Provinces in southern China, central and northern Thailand and northern Vietnam, there is reasonable correspondence in the crop factor (and therefore evapotranspiration) estimated using the two approaches. The key conclusion is that the annualised models based on global data sets tend to overestimate annual water use in tropical regions where rainfall is concentrated in only a few months.

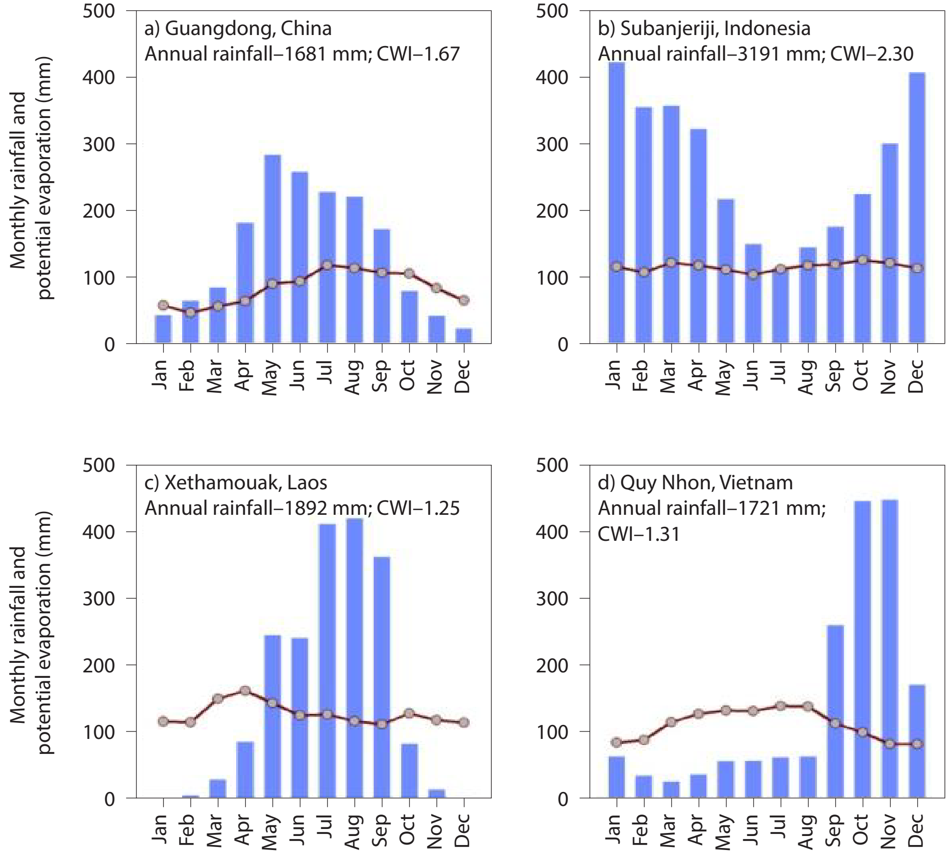


Figure 8. Average monthly rainfall and potential evaporation (FAO56) at four locations in South-East Asia where plantations are grown. Three of the locations: a) Guangdong, China; c) Xethamouak, Laos; and d) Quy Nhon, Vietnam have similar annual rainfall but this rainfall is much more uniformly distributed throughout the year at Guangdong than at the other locations. The model described by Figure 6 would predict, for a given soil water holding capacity, higher plantation evapotranspiration (and average crop factor) at Guangdong than at Quy Nhon or Xethamouak.

4.2 Inter-annual variation in rainfall and plantation water use

The preceding analysis was based on water use by plantations in an average year. Monthly rainfall varies sharply both within and between years. To explore the effect of this variation in rainfall, water use by a closed canopy *Eucalyptus* plantation (same soil characteristics as above) is estimated for each of 15 years at one location in north Vietnam (Phu Tho, long-term average annual rainfall 1,392 mm) and another in central Vietnam (Quy Nhon, long-term average annual Rainfall 1,721 mm), commencing in 1999.

For the period 1999–2013, the annual rainfall varied from 1,045 to 1,892 mm (average 1,383 mm) at Pho Tho and 1,497 to 3,169 mm (average 2,262 mm) at Quy Nhon. Average annual rainfall from 1999–2013 was lower at Pho Tho than the long-term average, and predicted plantation water use was between 55 and 90 % of rainfall (Figure 11). For the same period, average annual rainfall at Quy Nhon

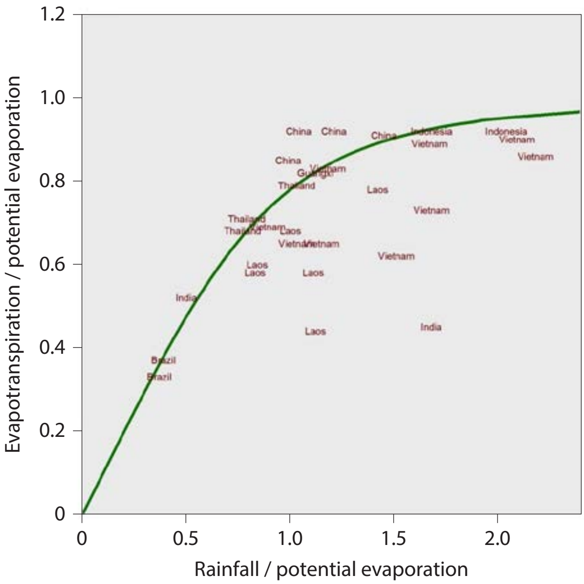


Figure 9. The relationship between the crop factor (evapotranspiration / potential evaporation) and climate wetness index (rainfall / potential evaporation). The data points are labelled by country and are estimates of the crop factor made using the vegetation characteristics in Figure 5. The line is the curve for plantations from Zhang et al. (2004) that is also shown in Figure 2.

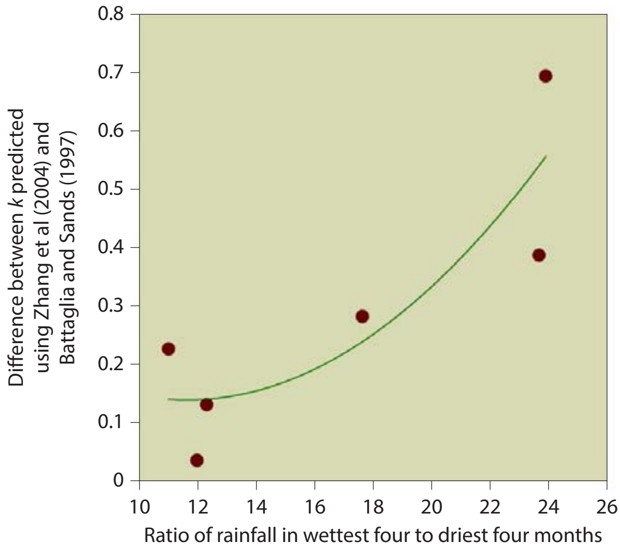


Figure 10. The relationship between the difference in the crop factor estimated using Zhang et al (2004) and the vegetation characteristic in Figure 3, plotted as a function of the ratio of rainfall in the wettest four to the driest four months. The discrepancy between k predicted by the two models increases with this measure of rainfall seasonality.

was higher than the long-term average. This was due to several very wet months (>750 mm) late in each of 2008, 2009 and 2010. In these years, estimated plantation water use at Quy Nhon was about 40% of rainfall but in a dry year, with a more uniform distribution of rainfall, plantation water use was 90% of rainfall.

Rainfall is highly variable within and between years, and evapotranspiration estimated using average or median rainfall data does not provide a complete understanding of the potential effects of plantations on steam flow. In Section 4.3, evapotranspiration and the ratio of evapotranspiration to rainfall are calculated for the 10th percentile and 50th percentile rainfall record in each of the major plantation regions in Thailand, Vietnam, Guangxi Province in China, Indonesia and Laos.

4.3 Plantation water use by climate type, country and location

Climatically, northern Laos and northern Vietnam have more in common with Guangxi Province in China than with either southern Laos or central Vietnam. Similarly, southern Laos is more similar to central Thailand than it is to northern Laos. The results in the rest of this section are therefore organised into Koppen's climate types (Koppen 1900). The Koppen classification is the most widely used system in climatology, particularly in relation to crop suitability and productivity, and is an output of the FAO LocClim climate tool (Greiser 2006). The classification was recently updated (Kottek et al. 2006). The areas where plantations of *Eucalyptus* are established in South-East Asia occur in six Koppen climate types.

1. Equatorial, fully humid
   This applies to Sumatra, Kalimantan, western Java and parts of Malaysia. The mean temperature in the coldest month is >18°C and the average rainfall of the driest month exceeds 60 mm (Kottek et al. 2006).
2. Equatorial, savannah, dry summer
   This climate type occurs in southern parts of Thailand, Laos and Vietnam. The mean temperature in the coldest month is still >18°C but rainfall in the driest months (during summer) is less than 60 mm (Kottek et al. 2006).
3. Equatorial, savannah, dry winter
   This climate type occurs in central Laos and in central and north-eastern Thailand. The same as Equatorial, Savannah, Dry Summer but in these climates the driest months occur in winter (Kottek et al., 2006).
4. Warm temperate, fully humid, hot summer
   This climate type occurs in northern Guangxi Province, China and applies at Qipo Forest Farm. The mean temperature of the coldest month is between –3 and 18°C and rainfall in the driest month is more than 60 mm (Kottek et al. 2006).
5. Warm temperate, dry winter, hot summer
   Southern and coastal Guangxi and Guangdong provinces in China, and northern Vietnam and Laos experience this type of climate. The mean temperature of the coldest month is between –3 and 18°C and rainfall in the driest month is less than 60 mm (Kottek et al. 2006).
6. Warm temperate, dry winter, wet summer
   This climate occurs in south Vietnam. The mean temperature of the coldest month is between –3 and 18°C and rainfall in the driest month is less than 60 mm. More than two-thirds of rain falls during summer (Kottek et al. 2006).

Evapotranspiration was calculated for the average annual rainfall and potential evaporation in the main *Eucalyptus* plantation regions in South-East Asia. This was done using the *Eucalyptus* plantation water-use tool described in the previous section. The results are shown in Table 3 and the location of these plantation regions can be seen in Figure 12. The tool calculates monthly evapotranspiration and the relative soil water content at the end of each month. In most locations, predicted average annual evapotranspiration was less than 60% of annual rainfall. However, in central Thailand and Guangxi Province in China, annual evapotranspiration was generally more than 70% of annual rainfall. In these regions, annual evapotranspiration from paddy rice would be similar to that of *Eucalyptus,* and cassava or hill rice would still use more than 60% of annual rainfall. The importance of the predicted difference between land uses depends on the demand for water by other users.

For five locations, representing the range of climate types in South-East Asia, evapotranspiration was calculated for the 5th, 10th and 25th percentile and medial rainfall years. The 10th percentile year was used because it represents conditions that are expected once in every one or two rotations. Evapotranspiration was calculated in mm per year and as a percentage of annual rainfall (Table 4).

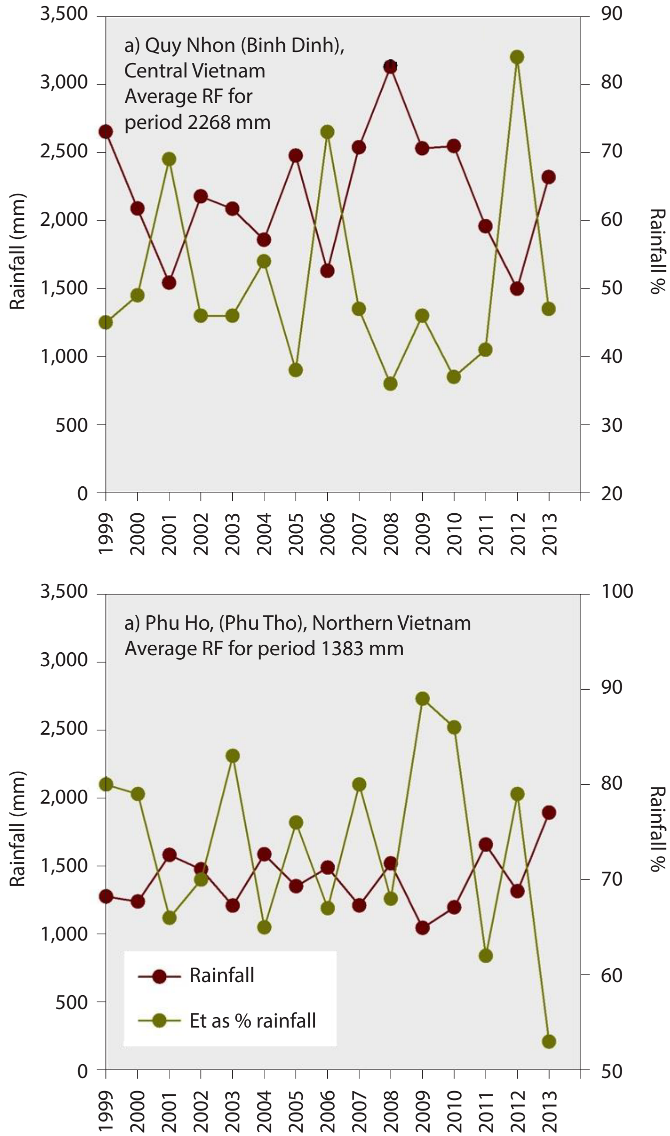


Figure 11. Annual rainfall and evapotranspiration expressed as a percentage of rainfall from 1999 to 2013 at two locations in Vietnam.

Table 3. Estimated evapotranspiration of *Eucalyptus* plantations (in mm and as a percentage of rainfall) calculated using the water-use tool and average annual rainfall. Locations are organised firstly by Koppen climate type and then by country. The climate wetness index and a drought index (the ratio of maximum plant-available water in 2 m of clay loam soil to the difference between potential evaporation and rainfall during the dry season) are also given. Plantations at sites with a drought index less than 0.3 experience severe water stress even in an average year. Locations where predicted evapotranspiration exceeds 80% of rainfall are highlighted in yellow.

Koppens climate type	Country	Location	Climate wetness index	Drought index	Evapotranspiration (median)	
					mm	% of rainfall
Equatorial, fully humid	Indonesia	Subanjeriji	2.3	>1	1345	48
		Pekanbaru	2.2	>1	1437	45
Equatorial, savannah, dry summer	Laos	Xepon	1.3	0.23	953	53
		Xethamouak	2.1	0.35	1026	42
	Vietnam	Da Nang	1.3	0.23	953	53
		Phu Yen	1.2	0.19	903	59
		Quy Nhon	1.3	0.20	907	53
Equatorial, savannah, dry winter	Laos	Attopeu	1.6	0.17	983	38
		Pak Lai	1.1	0.24	899	63
		Savannakhet	0.9	0.16	942	66
		Thakhek	1.7	0.21	900	38
	Thailand	Chachoengsao	0.9	0.19	1051	76
		Chiang Mai	0.9	0.23	893	75
		Nahkon Ratchasma	0.8	0.20	914	85
	Vietnam	Phon Hong	1.7	0.21	843	38
Warm temperate, fully humid, hot summer	China	Nanning	1.2	0.65	1104	84
Warm temperate, dry winter, hot summer	China	Beihai	1.3	0.36	1125	66
		Guangzhou	1.7	0.76	1007	60
		Zhanjiang	1.3	0.51	1206	73
		Zhangzhou	1.1	0.44	1223	80
	Laos	Pak Sane	2.4	0.30	1016	33
		Xieng Khuong	1.7	0.39	909	51
	Vietnam	Phu Tho	1.9	>1	1039	55
		Quan Ninh	2.4	0.63	936	40
		Hue	2.5	0.45	1079	37
		Khanh Hoa	0.9	0.17	929	71

At first glance, it is hard to see patterns in the data presented in Table 4. For example, at Nanning in Guangxi Province, China, predicted evapotranspiration is a bigger percentage of rainfall in the 10th percentile year than in the 5th percentile year. This apparent paradox occurs because the years in the climate record are ranked by annual rainfall which gives no indication of the way that rainfall is distributed. The rain in the 10th percentile year at Nanning was more uniformly distributed throughout the year than in either the 5th or 25th percentile years. The results of this analysis are now summarised below by Koppen climate type.

1. Equatorial, fully humid—Sumatra, western Java, Kalimantan, Malaysia

   Even in dry years, predicted evapotranspiration by *Eucalyptus* plantations in Sumatra (equatorial, fully humid) is between 50 and 60% of rainfall.

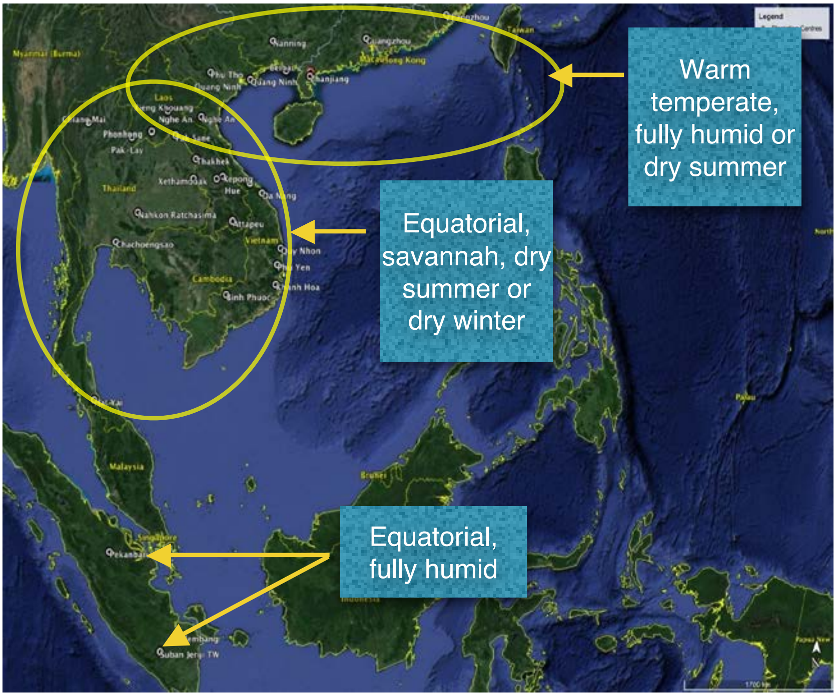


Figure 12. Map of South-East Asia showing the major plantation growing areas grouped by Koppen climate types.

Table 4. Estimated evapotranspiration of *Eucalyptus* plantations, in mm and as a percentage of rainfall, for the 5th, 10th and 25th percentile rainfall in locations in South-East Asia that are representative in the region of the main Koppen climate types.

Climate type	Example	For 5th percentile rainfall			For 10th percentile rainfall			For 25th percentile rainfall		
		Rain mm	Et Mm	% rain	Rain mm	Et mm	% rain	Rain mm	Et mm	% rain
Equatorial, fully humid	Subanjeriji, Indonesia	2122	1268	60	2286	1258	55	2490	1437	58
Equatorial, savannah, dry winter	Chachoengsao Thailand	1300	844	65	1392	997	72	1532	1054	69
Equatorial, savannah, dry summer	Quy Nhon Vietnam	1443	863	60	1484	830	56	1577	858	55
Warm temperate, fully humid	Nanning China	1029	768	75	1115	1100	>95	1248	916	74
Warm temperate, dry summer	Phu Tho Vietnam	1313	903	69	1368	888	65	1512	880	58

In these areas, the establishment of *Eucalyptus* plantations will not have a major effect on stream flow.

2. Equatorial, savannah, dry summer or dry winter
   Southern Laos and Vietnam and central and northern Thailand experience an equatorial savannah climate (average temperature of coolest month >18°C) with either a dry summer or winter (rainfall in the driest month is less than 60mm). Predicted evapotranspiration in an average rainfall year was less than 72% of rainfall at all of the selected locations. At Chachoengsao in Thailand, where predicted average evapotranspiration is a bigger percentage of annual rainfall than in other locations in this climate type (Table 3), predicted evapotranspiration for the 5th, 10th and 25th percentile years was 65, 72 and 69% of rainfall respectively (Table 4).

   Northern Thailand and some parts of southern Laos (Xepong, Xethamouak) and central Vietnam (Da Nang and Phon Hong) experience a very severe dry season and the ratio of plant-available soil water to dry-season evaporation deficit is approximately 0.2 for a 2 m soil. At these sites, *Eucalyptus* plantations will experience severe water stress in some years.

3. Warm temperate (fully humid or dry winter).
   Northern Laos, northern Vietnam and south-western China experience temperate climates that are either fully humid (Nanning) or experience a dry winter. In these regions, rainfall is more uniformly distributed throughout the year and predicted rates of evapotranspiration in median rainfall conditions are generally above or close to 1,000 mm and less than 70% of rainfall. Nanning and Zhanzhou in southern China are exceptions, and even in an average year, predicted evapotranspiration exceeds 80% of rainfall. At Nanning, predicted evapotranspiration for the 5th, 10th and 25th percentile year at Chachoengsao was 75, 95 and 74% of rainfall respectively (Table 4). In the warm temperate, fully humid climate of northern Guangxi, rainfall is quite uniformly distributed throughout the year and in some years (one in 10) predicted evapotranspiration exceeds 95% of rainfall (Table 3).

Section 4 summary: Water use by *Eucalyptus* plantations in South-East Asia

- The annualised model of Zhang et al (2004) describes the upper boundary of the relationship between the crop factor and climate wetness for plantation growing regions in South-East Asia.
- For some regions (Laos, central Vietnam, and central and northern Thailand) this annualised approach overestimates plantation water use. The discrepancy is largest for regions that have a pronounced dry season.
- The plantations of South-East Asia are grown in three broad climate types.
  - ◦ Equatorial, fully humid
    - In these climates (parts of Indonesia and Malaysia) water is not scarce and plantation establishment does have a major effect on annual stream flow.
  - ◦ Equatorial, savannah (with a pronounced dry season in either winter or summer)—central and northern Thailand, southern Laos and central Vietnam
    - Rainfall is very seasonal and although plantations of Eucalyptus use more water than annual crops, their total water use is still less than 70% of rainfall, even in dry years.
    - In these areas, plantations will experience drought stress and mortality is likely if plantations are established on shallow, skeletal soils.
  - ◦ Warm temperate (fully humid and with a pronounced dry season)—southern China and northern Laos and Vietnam
    - In northern Laos and Vietnam, the rainfall is still very seasonal and plantations will not have a major effect on annual stream flow.
    - In southern China, rainfall is more uniformly distributed throughout the year, and in northern Guangxi, plantations may have an important effect on annual stream flow in one in 10 years.

5 Plantation management in South-East Asia: water issues

5.1 When and how are eucalypts different to other crops?

Steady-state models based on global data sets (Zhang et al. 2004) overestimate annual evapotranspiration by *Eucalyptus* plantations in parts of South-East Asia with a pronounced dry season. This does not mean that *Eucalyptus* plantations will not use more water than alternative land uses. The models of Zhang et al. (2004) and the simple water balance calculator developed here predict a similar proportional increase in annual evapotranspiration where *Eucalyptus* plantations replace annual crops or pastures. Although this difference is small relative to the annual total evaporation from land covered with either vegetation type, it may nonetheless be important. The difference between water use by *Eucalyptus* plantations and annual crops and pastures is due to two key differences between *Eucalyptus* plantations and these alternative land uses. Firstly, *Eucalyptus* plantations are perennial, evergreen and their root systems are deeper than annual plants. Secondly, *Eucalyptus* plantations are aerodynamically rough, and this characteristic generates greater turbulence than is observed above smoother annual crops, enhancing evapotranspiration.

The deep-rooting habit and perennial status of *Eucalyptus* affects the seasonal pattern of water use by *Eucalyptus* compared to other crops. Throughout tropical South-East Asia, the maximum crop factor of paddy rice, cassava, sugarcane, maize and *Eucalyptus* is approximately one (see Section 4). During the wet season, all of these crops use water at rates that approximate reference evaporation. Late in the dry season, evapotranspiration from all of these crops is limited by available water. Despite this limitation, some evapotranspiration continues and this has been observed in *Eucalyptus* and from land that grew cassava, rice, maize and sugarcane during the wet season. In seasonally dry tropical and monsoonal climates, the main hydrological differences between plantations of *Eucalyptus* and alternative land uses are likely to occur during the 'shoulder seasons' or in the transition from the wet to the dry season and back again.

When the wet season ends, evapotranspiration from *Eucalyptus* plantations will continue at the maximum rate until a threshold soil water content is reached, after which a range of tree responses to soil drought act to reduce transpiration. Principal among these are stomatal closure and leaf shedding. Any reduction in leaf area will also reduce the interception of dry-season rainfall. Soil evaporation will also decrease when the surface is dry. The vegetation characteristic (Figures 5 and 6) integrates all of these responses in a single relationship between evapotranspiration and relative plant-available soil water. In Mediterranean environments, the vegetation characteristics of wheat, clover and lucerne were very similar to *E. globulus* and therefore to the tropical *Eucalyptus* plantations of South-East Asia (Ward et al. 2002). In the transition from the wet to the dry season, the rate of reduction in the crop factor is determined by the amount of soil-stored water that is available to vegetation. For example, Ward et al. (2002) observed that differences in annual evapotranspiration between annual (clover) and perennial (lucerne) pastures was equal to the difference in the amount of soil-stored water the root systems could access. Differences in rooting depth are an important factor influencing seasonal patterns of water use in plantations, crops and annual and perennial pastures. An example of the effect of differences between rooting depth on the evapotranspiration of cassava and *Eucalyptus* plantations is shown in Figure 13. Monthly rainfall and potential evaporation are shown together with evapotranspiration for a plantation with access to 3 m of clay loam and for cassava on the same site. Estimated annual evapotranspiration for plantations and cassava was 1,030 and 935 mm

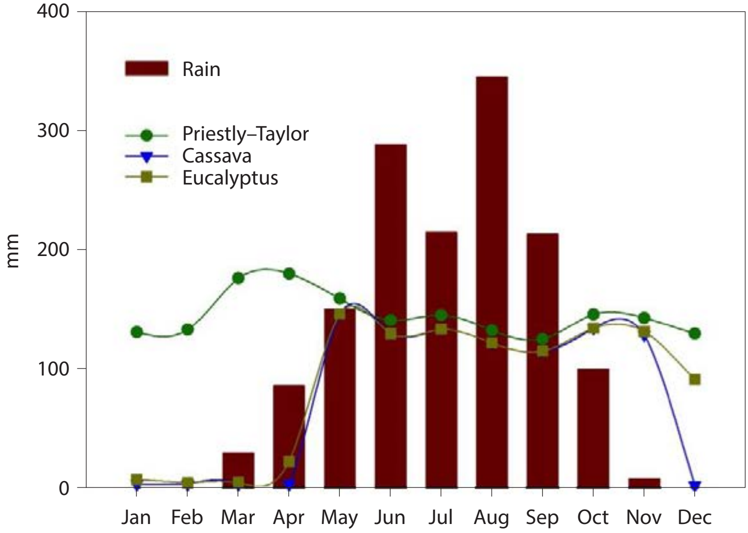


Figure 13. Estimated monthly evapotranspiration for *Eucalyptus* plantations and cassava at Savannakhet in Laos compared to rainfall and Priestley-Taylor potential evaporation (Priestley and Taylor 1972). In the dry season, plantation water use decreases more slowly than cassava water use due to the greater effective rooting depth of the plantation.

respectively and all of the difference between these crops occurred in December and April, the beginning and end of the dry season.

Effective rooting depth is an important determinant of variation in annual evapotranspiration between *Eucalyptus* and alternative land uses. The indeterminate growth habit of *Eucalyptus* species is another. *Eucalyptus* can grow and transpire at any time during the year when temperature and moisture limitations support positive net carbon assimilation. Annual pastures and crops dry out and many other plantation species, such as teak, which are deciduous, close their stomata at higher soil water content than *Eucalyptus*. Thus, water use by *Eucalyptus* will be greater than alternatives when the dry season is broken by unseasonal rain.

5.2 Drought risk in Laos, Thailand and central Vietnam

In April 2014, during a visit to a plantation of *E. camaldulensis* × *E. urophylla* hybrid near Vientiane in Laos, it was found that some trees had died from drought stress. In the latter half of the 2013–2014 dry season, *E. urophylla* and Acacia hybrid (*A. mangum* × *auriculiformis*) suffered widespread drought mortality in the central Vietnamese province of Binh Dinh (Figure 14). While there are no systematic data to relate mortality to soil depth or other site management practices, most of the plantations that were killed by drought were established on shallow, skeletal soils in the hills to the west of Quoy Nhon and Da Nang (Figure 14). Better site selection could no doubt have avoided or at least reduced these drought deaths. Water stress during the dry season is an important constraint on plantation productivity in central Vietnam and in central and southern Laos, and drought-induced mortality is likely to continue unless a minimum soil depth is included as a criterion in site selection.

One measure of dry-season severity is the ratio of maximum plant-available soil water to the cumulative dry-season difference between rainfall and potential evaporation. This index was calculated for the major plantation regions in South-East Asia (Table 3) and the results demonstrate that plantations on shallow soils may be exposed to severe water stress in southern Laos and central Vietnam.

Figure 14. A patch of drought mortality in an *E. urophylla* plantation near Quy Nhon, Binh Dinh Province, Vietnam.

5.3 Vegetation management, water use and water productivity

The ratio of evaporative 'losses', including understorey water use to transpiration, is an important determinant of plantation production and water productivity in water-limited situations (Equation 10, Section 6). Managing competition by understorey for water, particularly in the crucial transition from wet to dry seasons, will be important for maximising productivity.

Harwood and Nambiar (2014) raised weed control as a central issue for sustainable production systems in South-East Asia. In Malaysia, Thailand, Vietnam and Laos, many plantation growers cultivate (plough) the inter-row of their plantations during the first one to two years after establishment. This is done to mitigate fire risk and to prepare for planting of cassava and hill rice between wide-spaced trees in Laos. Repeated cultivation can destroy soil structure, reduce soil organic matter content and infiltration, and promote erosion (Harwood and Nambiar 2014) and therefore reduce productivity.

Poor weed control can reduce production and water productivity by increasing the ratio of losses to crop tree transpiration. The plantation at Qipo Forest Farm had a very dense weed layer. Leaf area was not measured in this experiment but the understorey was very dense and had a leaf area index equal to or greater than the plantation of *E. urophylla* (Figure 16). Average daytime solar radiation was 140 Wm^{-2} outside and 60 Wm^{-2} beneath the tree canopy; on average 43% of solar radiation penetrated the canopy. Using Beers Law (Saeki 1960) the leaf area index of the plantation was estimated to be 1.6. Understorey water use from July 2013 to June 2014 was 303 mm and the monthly total varied from 7 to 35 mm (Figure 16). This was more than one-third of total plantation water use and only 45 mm less than the annual crop tree transpiration. Plantations in tropical environments grow very quickly, and effective weed control in the first two years after planting has the potential to increase production and water productivity appreciably. For example, weed control at Qipo could have increased leaf area index by 100%, wood production by as much as 50% and water productivity by about one-third. This must be balanced against the cost of weed control and the potential for increased erosion prior to canopy closure. Understanding the benefits and costs of alternative weed control measures is a crucial issue requiring systematic investigation in South-East Asia.

Figure 15. This picture of Qipo Forest Farm near Nanning in Guangxi Province, China shows the very dense understorey that has developed under the plantation of *E. urophylla.*

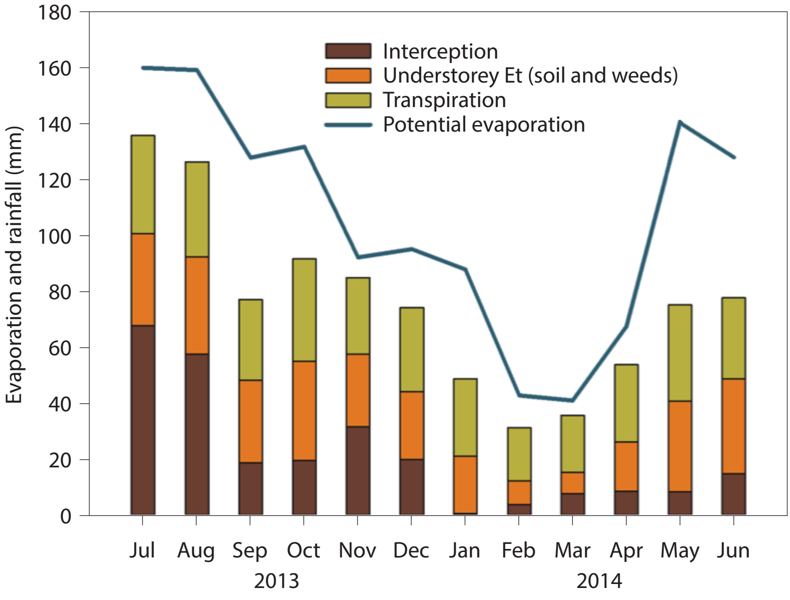


Figure 16. Potential evaporation, plantation transpiration, interception and understorey evapotranspiration measured at Qipo Forest Farm near Nanning, Guangxi Province, China. The measurements were made in a plantation of *E. urophylla* × *grandis.*

5.4 Agroforestry systems in Laos and Thailand

Agroforestry systems that combine plantations with crops are common in Thailand and Laos. Two companies growing *Eucalyptus* plantations in Laos are establishing these plantations at row spacing of 9 m and local people grow crops of cassava and hill rice in the space between the rows for at least the first two years after tree planting (Figure 17). In Thailand, crops are also grown in the first year after planting *Eucalyptus* plantations. In Thailand, *Eucalyptus* trees are grown in plantation blocks and in single or double rows on paddy bunds (Figure 18).

Trees planted at wide spacing and adjacent to paddy bunds have access to a larger soil volume than trees on blocks. They also use irrigation water from within the bund at the commencement of the dry season (Wongprom 2012). While individual trees use more water than those in block plantings, the total area-based water use of agroforestry systems is generally intermediate between crops and block plantings. Detailed nutrient and water balance studies are required to determine if the use of water by trees and crops is complementary or competitive.

In central and northern Thailand, it was found that *Eucalyptus* trees planted on paddy bunds did not reduce the productivity of paddy rice (Luangviriyasaeng 2009) or cassava (Wongprom et al. 2012). At Chachoengsao in central Thailand, the annual water use of clone K51 (*E. camaldulensis*) in the third year after planting was between 3,050 and 3,450 L per tree per year on the paddy bund and between 1,210 and 1,504 L per tree per year in a block planting (Wongprom et al. 2012). The block planting was stocked with 2,000 stems per ha^{-1} and annual transpiration was about 250 mm. On a crown drip line area basis, transpiration of the trees on the paddy bund was at least 500 mm per year. The daily rate of water use per tree varied fourfold between the start (20 L per day) and end of the dry season (<5 L per day). Even on paddy bunds, *Eucalyptus* trees are water limited during the dry season in northern and north-eastern Thailand (Wongprom 2012).

5.5. Area planted

The proportion of the landscape planted varies from very small percentages in Laos and much of Thailand (<5%) to intermediate amounts in

Figure 17. *Eucalyptus urophylla* × *camaldulesis* with wide spacing between rows and with four rows of recently planted cassava. This picture was taken near the end of the dry season. The sandy soil was very dry and a number of trees in this stand had already died of drought stress in April 2014.

Vietnam (catchments with >20% plantation cover are not uncommon) and much larger proportions of catchments are planted in Sumatra and in some areas of northern Guangxi, China. Harwood and Nambiar (2014) observed that some catchments in China are completely planted from the ridge top to the valley floor. Planting full catchments in northern Guangxi will result in an increase in average annual evapotranspiration of between 5% (dry years) and 10% (wet years) compared to the degraded natural forests and poor pine and fir plantations they have often replaced. In average and above average years, there will still be plenty of stream flow, but in dry years this small increase in evapotranspiration may reduce stream flow by half, albeit from a very low base. In water-limited areas, the effect of plantations on stream flow could be mitigated by avoiding riparian zones, drainage lines and other wet areas such as seeps caused by dykes (Gilfedder et al. 2010). The practice of planting entire catchments is likely to cause conflict in drought years if usually permanent streams cease to flow in the dry season.

Figure 18. A row of *E. camaldulensis* × *urophylla* on a paddy bund near Chachoengsao in central Thailand. A block planting of *Eucalyptus* can be seen in the background. Trees on these paddy bunds use more than twice the amount of water as trees in the nearby block, without any adverse effect on rice production.

Section 5 summary: Plantation management in South-East Asia: water issues

- Water use during the wet season and at the end of the dry season is similar for *Eucalyptus* plantations, cassava, paddy rice and maize.
- Plantations use more water than the main alternative land uses in the transition from wet to dry seasons. The duration of the difference will depend on the effective rooting depth of the plantations.
- In southern Laos and southern and central Vietnam, there is a very sharp and often quite long dry season. In these areas, *Eucalyptus* plantations will experience some drought stress and some drought mortality may occur in dry years and on shallow, skeletal soils.
- Weed management prior to canopy closure is a crucial issue in South-East Asia. Cultivation is often used but this destroys soil structure, reduces infiltration and increases erosion. Poor weed control will increase evaporative losses by as much as 50%. This must be balanced against the cost of weed control and the potential for increased erosion prior to canopy closure. Understanding the benefits and costs of alternative weed control measures is a crucial issue requiring systematic investigation in South-East Asia.
- *Eucalyptus* trees on paddy bunds use more water than trees in blocks but did not affect rice yield in a study in central Thailand.
- Agroforestry systems in Laos will use water at a per hectare rate that is intermediate between a block planting and the crop planted.

6 Plantation water productivity

Quantifying water use does not provide a sufficient basis for making land-use decisions. Wood production and value generated from water use must also be considered, particularly where allocable water is limited. A lot has been written about 'water-use efficiency' of plantations and most of the published data are actually transpiration efficiency of net carbon assimilation (e.g. Ngugi et al. 2003; Searson et al. 2004; Grossnickle et al. 2005) or above-ground biomass growth. If the aim is to design water-use efficient landscapes that combine many land uses for maximum community benefit, then it is very important to understand the distinction between wood production per unit of evapotranspiration (plantation water productivity) and transpiration efficiency.

6.1 Plantation productivity

Wood yield of a plantation (W, g) can be expressed as the product of transpiration (T_{TREE}; kg H_2O), the transpiration efficiency of dry-matter accumulation (TE_{DM}; expressed in g DM kg^{-1} H_2O) and the proportion of this dry-matter partitioned to wood (HI; g g^{-1}) and is given by Equation 8 which is adapted from Passioura (1977) and Passioura and Angus (2010).

$$W = TE_{\mathrm{DM}} \times T_{\mathrm{TREE}} \times HI \qquad \text{Equation 8}$$

6.2 Plantation water productivity (water-use efficiency of wood production)

The water productivity of a plantation (PWP_{WOOD}) is the ratio of wood production to evapotranspiration and is given by Equation 9. This expression can be transposed to Equation 10 in which the effects of the transpiration efficiency of dry matter, the harvest index and the ratio of other evaporative fluxes to crop tree transpiration can be easily visualised (White et al. 2014).

$$PWP_{\mathrm{WOOD}} = \frac{TE_{\mathrm{DM}} \times T_{\mathrm{TREE}} \times HI}{T_{\mathrm{TREE}} + I + S + T_{\mathrm{WEED}}} \qquad \text{Equation 9}$$

$$PWP_{\mathrm{WOOD}} = \frac{TE_{\mathrm{DM}} HI}{1 + \frac{T_{\mathrm{WEED}} + I + S}{T_{\mathrm{TREE}}}} \qquad \text{Equation 10}$$

It is clear that transpiration efficiency of dry-matter production is one of several factors that affect plantation water productivity. To design water-productive landscapes and ensure water security for local people requires an understanding of the effect of available water and plantation management on all the factors that affect productivity, and on all the components of evapotranspiration.

6.3 Managing plantation water productivity: stand scale

Increasing the transpiration efficiency of dry-matter production, increasing the proportion of dry matter that is allocated to stem wood or decreasing the ratio of evaporative losses to crop tree transpiration are all potential mechanisms for increasing plantation yield and plantation water productivity (Equation 10). Managing these processes in isolation from one another might create unintended consequences as they are not independent. For example, increased transpiration efficiency of dry-matter production will often be associated with water limitation and a reduced proportional allocation of dry matter to wood (Ryan et al. 2010). Thus, transpiration efficiency of dry-matter production is often negatively correlated with plantation water productivity (White et al. 2009a).

Evaporative losses due to soil evaporation, weed transpiration and canopy interception can make up more than half of the total stand water use (Figure 16). Reducing their contribution to evapotranspiration is perhaps the most straightforward means of improving water productivity. In recent reviews for agricultural systems, Blum (2009) and Passioura (2006) argued that managing canopy development to increase the proportion of evapotranspiration that occurs as transpiration may be a more effective route to manipulating water-use efficiency than the alternatives of attempting to improve transpiration efficiency or to reduce transpiration. At Qipo Forest Farm in Nanning (Figure 16), reducing weed transpiration and soil evaporation has the potential to increase productivity by up to 30% but would also dramatically increase the water productivity of that plantation by reducing the ratio of evaporative losses to transpiration (Equation 10).

Evapotranspiration (the total water use of the system) is conservative over the longer term (Kelliher et al. 1995; Drake et al. 2012) and difficult to influence through plantation management. It is largely a function of rainfall and available energy, and the components of evapotranspiration tend to compensate for one another. For example, changes in management may reduce evapotranspiration in the short term (for example by reducing leaf area through thinning or pruning) but changes in the system (increased understorey leaf area) mean that over longer periods, total water use remains similar. It may be best to focus efforts on maximising productivity on land where plantations are grown and to manage water use through landscape design at larger scales. This approach will minimise evaporative losses and maximise plantation water productivity.

Rather than focus on transpiration efficiency, it is more direct to target water productivity (wood production per unit of evapotranspiration) which integrates the effect of management on all of the components of evapotranspiration as well as on the transpiration efficiency of dry-matter production and the allocation of dry matter to wood and other biomass components. Recent research in temperate (White et al. 2014) and tropical (Stape et al. 2004) systems has shown that plantation water productivity is correlated with both production and water use. This is important as it offers potential for plantation managers and water planners to reconcile wood production from *Eucalyptus* plantations with the allocation of limited water resources. Maximising productivity through tree breeding or silviculture will also maximise plantation water productivity.

There are numerous tree improvement and management pathways to increase the water productivity of plantations. However, it is difficult for growers, water planners or policy makers to distill patterns from the complexity. Nonetheless, these patterns exist and there is evidence (Stape et al. 2004, 2008; White et al. 2014) that both growth and water productivity are positively correlated with water use. If this relationship is general then managing plantations to maximise growth will also maximise the amount of wood produced from the use of a unit of water.

At the stand scale, the solution is therefore relatively straightforward. All of the complexity in variability of productivity and water use with climatic and site characteristics can be reduced to the following statement: 'managing plantations to maximise their growth will also maximise water productivity'.

6.4 Managing plantation water productivity: catchment scale

At the landscape scale, the problem of managing the relationship between productivity and water use is much more complex than at the stand scale. In a modeling analysis, Gilfedder et al. (2010) showed that plantations on wet areas, such as concave slopes, deeper soils or riparian zones, had a greater predicted impact on stream flow per area planted than those on steep slopes and in ridge-top positions. The same analysis suggested that these plantations in wet areas were more productive per unit water used. This is consistent with studies in temperate *E. globulus* (White et al. 2014) and tropical *E. urophylla* × *grandis* (Stape et al. 2004; Stape et al. 2008) systems which found that plantation water productivity was positively correlated with plantation water use. Optimising the design of landscapes that include plantations requires consideration of many values, including biodiversity, amenity, productivity and water resources. However, these results highlight the importance of balancing the potential water impacts of plantations with a consideration of productivity. For example, it may be possible to minimise the water impacts of growing a given volume of wood at the catchment scale by establishing plantations to grow that wood in areas where their evapotranspiration is greatest. Reducing planted area but selecting areas where water use is greatest may be one option for managing the trade-off between wood production and water use at the catchment scale.

Section 6 Summary: Plantation water productivity

- Plantation water productivity is affected by three main factors: the transpiration efficiency of dry-matter production; the proportional allocation of dry matter to wood; and the ratio of evaporative losses to transpiration.
- At the stand scale, all of the complexity in the variation of productivity and water use with climatic and site characteristics can be reduced to the following statement: 'managing plantations to maximise their growth will also maximise water productivity'.
- Reducing planted area but selecting areas where water use is greatest may be one option for managing the trade-off between wood production and water use at the catchment scale.

Conclusions

The main goal of this project was to provide information and tools to assist natural resource managers and decision makers in South-East Asia to make informed decisions on the impacts of plantation establishment on water availability and ensure security of supply for all users. This has been done by synthesising current knowledge on water use by *Eucalyptus* plantations and through developing a simple tool that can be used to quantify annual and monthly water use by existing or planned plantations. This tool has already been made available to all who assisted with the project and can be made available to other interested parties.

This section restates the main conclusions that can be drawn about the impact of *Eucalyptus* plantations on water resources in South-East Asia. These statements are not intended as the final word. For example, the understanding of the impacts of vegetation on flow duration and dry-season flow is poor and definitive research may result in changes to the following statements. Nonetheless, these statements provide a reasonable basis for understanding and managing the relationships between plantations and stream flow in South-East Asia and southern China.

I. In South-East Asia, there is a great deal of concern about *Eucalyptus* water use, particularly in government departments. Water is a crucial resource and any real or perceived threat to security evokes a strong community and government reaction. With the exception of potential reduction in dry-season stream flow in Thailand, Laos and central and south Vietnam, concerns expressed by community and government about the effects of *Eucalyptus* on water resources is out of proportion to the risk, which is generally low.

II. The total water use of any land use (evapotranspiration) is the sum of transpiration, soil evaporation and canopy interception. Very few, or at least a low proportion, of the many studies of crop or plantation water use actually report all the fluxes. Most report only transpiration, which is often less than half of the total water use. Incomplete water balances should not be used to quantify and assess the comparative effects of alternative land uses on stream flow.

III. Vegetation cover is a less important determinant of evapotranspiration (water use) than climate or hydrogeology. Nonetheless, small proportional or absolute differences between vegetation types can, under some circumstances, result in reductions in stream flow.

   a. On average, plantations of perennial trees use more water than natural forest or annual pastures.
   b. The difference in water use between plantations and other vegetation is generally less than 10% and never more than 20%.
   c. There is no clear evidence that plantations of *Eucalyptus* use more water per year than either *Pinus* plantations or other types of tree plantations, including rubber.

IV. The climate wetness index (ratio of rainfall to potential evaporation) is a good variable for making an initial assessment of where plantations of any species are likely to cause water scarcity.

   a. Where the climate wetness index is greater than 1.5, the annual run-off from any land use will be large, even in 'dry' years. This includes all of Malaysia, southern Thailand, northern parts of Vietnam and Laos, some parts of southern China (most of Guangdong Province) and Kalimantan, Sumatra and western Java. Plantations will not have an important effect on water resources in these regions.
   b. Evapotranspiration is most sensitive to land use when the climate wetness index is 1.0 and water use by plantations should be carefully analysed wherever the climate wetness index is between 0.7 to 1.3. This includes central and northern Thailand, southern Laos, central Vietnam and much of Cambodia. Much of

Sections 4 and 5 of this report were devoted to this analysis (see point v and vi below).

V. In areas with a climate wetness index between 0.7 and 1.3 (central and northern Thailand, southern Laos, central Vietnam and much of Cambodia) the effect of plantations on annual stream flow and evapotranspiration was lessened by the extremely seasonal distribution of rainfall. Even in very dry years, predicted evapotranspiration was (but not always) less than 70% in more than 95% of years (see Table 4 for details).

VI. In northern Guangxi Province, China, rainfall is more uniformly distributed and plantations (if they occupy all of a catchment) may have important effects on stream flow in one in 10 years.

VII. Weed management prior to canopy closure is a crucial issue in South-East Asia. Cultivation is often used but this destroys soil structure, reduces infiltration and increases erosion. Poor weed control will increase evaporative losses by as much as 50%. This must be balanced against the cost of weed control and the potential for increased erosion prior to canopy closure. Understanding the benefits and costs of alternative weed control measures is a crucial issue requiring systematic investigation in South-East Asia.

VIII. Water stress during the dry season is an important constraint on plantation productivity in central Vietnam and in central and southern Laos, and drought-induced mortality is likely to continue unless a minimum soil depth is included as a criterion in site selection.

IX. Water productivity (wood production per evapotranspiration) is correlated with water use. This greatly simplifies the objectives of breeding and silviculture for water-use efficiency in tropical plantations. Strategies to maximise production and value will also maximise water productivity (yield per water use) and economic water productivity (value per water use) of plantations. In seasonally dry environments, this will also increase drought risk which can be mitigated by good site selection, vegetation management and suitable stocking levels.

7.1 Important knowledge gaps

There are still some crucial knowledge gaps that prevent a complete analysis of all aspects of plantation impacts on water resources.

Understanding of the effect of plantations and alternative land uses on stream-flow duration and on dry-season flow. More precise measurement techniques must be developed so that the effect of vegetation cover on dry-season flow can be quantified.

The transition from the wet to the dry season has been under-researched in South-East Asia and elsewhere.

Vegetation management is a key issue for South-East Asia. Strategies must be found for managing fire risk without putting soil resources at risk. These strategies must account for the potential reduction of both production and water productivity if strong weed competition develops.

References

Alados I., Foyo-Morenos I., Olmo F.J. and Alados Arboledas L. 2003. Relationship between net radiation and solar radiation for semi-arid shrub-land. Agricultural and Forest Meteorology 116, 221–227.

Allen R.G., Pereira L.S., Raes D. and Smith M. 1998. Crop evapo- transpiration: guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56.Food and Agriculture Organization of the United Nations: Rome.

Almeida A.C., Landsberg J.J. and Sands P.J. 2004. Parameterisation of 3-PG model for fast-growing Eucalyptus grandis plantations. Forest Ecology and Management 193, 179–195.

Almeida A.C., Soares J.V., Landsberg, J.J. and Rezende G.D. 2007. Growth and water balance of a Eucalyptus grandis hybrid plantation in Brazil during a rotation for pulp production. Forest Ecology and Management 251, 10–21.

Andreassian V. 2004. Waters and forests: from historical controversy to scientific debate. Journal of Hydrology 291, 1–27.

Battaglia M. and Sands P. 1997. Modelling site productivity of Eucalyptus globulus in response to climatic and site factors. Australian Journal of Plant Physiology. 24, 831–850.

Battaglia M., Sands P.J., White D.A. and Mummery D. 2004. CABALA: a linked carbon, water and nitrogen model of forest growth for silvicultural decision support. Forest Ecology and Management 193: 251–282.

Benyon R.G., Theiveyanathan S. and Doody T.M. 2006. Impacts of tree plantations on groundwater in south-eastern Australia. Australian Journal of Botany 54, 181–192.

Benyon R.G. and Doody T. M. 2014. Comparison of interception, forest floor evaporation and transpiration in Pinus radiata and Eucalyptus globulus plantations. Hydrological Processes 29(6), 1173–1187.

Blum A. 2009. Effective use of water (EUW) and not water-use efficiency (WUE) is the target of crop yield improvement under drought stress. Field Crops Research 112, 119–123.

Bosch J.M. and Hewlett J.D. 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. Journal of Hydrology 55, 3–23.

Bren L.J. 1993. Hydrologic effects of conversion of slopes of a eucalypt forest catchment to radiata pine plantation. Australian Forestry 56, 90–106.

Brooksbank K., White D.A., Veneklaas E.J. and Carter J.L. 2011. Hydraulic redistribution in Eucalyptus kochii subsp borealis with variable access to fresh groundwater. Trees, Structure and Function 25, 735–744.

Brown A.E., Zhang L., McMahon T.A., Western A.W. and Vertessy R.A. 2005. A review of paried catchment studies for determining changes in water yield resulting from alterations in vegetation. Journal of Hydrology 310, 28–61.

Brown A.E., Western A.W., McMahon T.A. and Zhang L. 2013. Impact of forest cover changes on annual streamflow and flow duration. Journal of Hydrology 483, 39–50.

Bruijnzeel L., Calder I.R. and Vertessy R. 2004. Impact of forest conversion on streamfow. Encyclopaedia of Forest Science 1, 350–358.

Budyko M.I. 1974. Climate and life. English ed. edited by David H. Miller. Academic Press: New York.

Calder I.R., Hall RL. and Prasanna K.T. 1993. Hydrological impact of Eucalyptus plantations in India. Journal of Hydrology 150,635–648.

Castelao A., Gonzalez M.A. and Paz A, 1996. Soil moisture depletion under Pine and Eucalypt plantations. Hydrology in the Celtic Countries, 167–173.

Cowan I.R. 1972. An electrical analogue of evaporation from, and flow of water in plants. Planta 106, 221–226.

Donohue R.J., Roderick M.L. and McVicar T.R. 2007. On the importance of including vegetation dynamics in Budyko's hydrological model. Hydrology and Earth System Sciences 11, 983–995.

Donohue R.J., McVicar T.R. and Roderick M.L. 2009. Climate-related trends in Australian vegetation cover as inferred from satellite observations, 1981–2006. Global Change Biology 15, 1025–1039.

Drake P.L., Mendham D.S., White D.A., Ogden G.N. and Dell B. 2012. Water use and water-use efficiency of coppice and seedling Eucalyptus globulus Labill.: a comparison of stand-scale water balance components. Plant and Soil 350, 221–235.

Dye P. 2013. A review of changing perspectives on Eucalyptus water-use in South Africa. Forest Ecology and Management 301, 51–57.

Dye P. and Versfeld D. 2007. Managing the hydrological impacts of South African plantation forests: an overview. Forest Ecology and Management 251, 121–128.

Farley K.A., Jobbagy E.G. and Jackson R.B. 2005. Effects of afforestation on water yield: a global synthesis with implications for policy. Global Change Biology 11, 1565–1576.

Fu B.P. 1981. On the calculation of the evaporation from land surface. Chinese Journal of Atmospheric Sciences 5.

Gilfedder M., Zhang L., Theiveyanathan T., Marcar N.E., Roxburgh S., Littleboy M., Zhao F., Chen Y., de Almeida A.C. and Crawford D.F. 2010. Methods to assess water allocation impacts of plantations: final report. CSIRO: Water for a healthy country national research flagship report series.

Greenwood A.J.B. 2013. Review: The first stages of Australian forest water regulation: national reform and regional implementation. Environmental Science and Policy 29, 124–136.

Grieser J. 2006. New LocClim 1.10—Local Climate Estimator. Food and Agriculture Organization of the United Nations: Rome.

Grossnickle S.C., Fan S. and Russell J.H. 2005. Variation in gas exchange and water use efficiency patterns among populations of western red cedar. Trees 19, 32–42.

Harwood C.E. and Nambiar E.K.S. 2014. Sustainable plantation forestry in South-East Asia. ACIAR Technical Report No. 84. Australian Centre for International Agricultural Research: Canberra.

Honeysett J.L., White D.A., Worledge D. and Beadle C.L. 1996. Growth and water use of Eucalyptus globulus and E. nitens in irrigated and rainfed plantations. Australian Forestry 59(2), 64–73.

Hubbard R.M., Stape J., Ryan M.G., Almeida A.C. and Rojas J. 2010. Effects of irrigation on water use and water use efficiency in two fast growing Eucalyptus plantations. Forest Ecology and Management 259(9), 1714–1721.

Jackson R.B., Jobbagy E.G., Avissar R., Roy S.B., Barrett D.J., Cook C.W., Farley K.A., le Maitre D.C., McCarl B.A. and Murray B.C. 2005. Trading water for carbon with biological carbon sequestration. Science 310, 1944–1947.

Kelliher F.M., Leuning R., Raupach M.R. and Schulze E.-D. 1995. Maximum conductances for evaporation from global vegetation types. Agricultural and Forest Meteorology 73, 1–16.

Koppen W. 1900. Versuch einer Klassifikation der Klimate, vorzugsweise nach ihren Beziehungen zur Pflanzenwelt. Geographische. Zeitschrift 6, 657–679.

Kottek M., Grieser J., Beck C., Rudolf B. and Rubel F. 2006. World map of the Koppen-Geiger climate classification updated. Meteorologische Zeitschrift 15, 259–263.

Landsberg J.J. and Waring R.H. 1997. A generalised model of forest productivity using simplified concepts of radiation-use efficiency, carbon balance and partitioning. Forest Ecology and Management 95, 209–228.

Lane P.N.J., Morris J., Ningnan Z., Guangyi Z., Guoyi Z. and Daping X. 2004. Water balance of tropical eucalypt plantations in south-eastern China. Agricultural and Forest Meteorology 124, 253–267.

Lane P.N.J., Best A., Hickel K. and Zhang L. 2005. The response of flow duration curves to afforestation. Journal of Hydrology 310, 253–265.

Lima W.d.P., Zakia M.J.B., Libardi P.L. and Souza Filho A.P.d. 1990. Comparative evapotranspiration of Eucalyptus, pine and natural cerrado vegetation measured by the soil water balance method. IPEF International, 5–11.

Luangviriyasaeng V. 2009. Growth of different eucalypt clones planted on paddy bunds. Thailand Journal of Forestry 28, 1–12.

Monteith J.L. 1965. Evaporation and environment. Symp. Soc. Exp. Biol. 19, 205–234.

Myers B.J. and Talsma T. 1992. Site water balance and tree water status in irrigated and fertilised stands of Pinus radiata. Forest Ecology and Management 52, 17–42.

Myers B.J., Benyon R.G., Theiveyanathan S., Criddle R.S., Smith C.J. and Falkiner R.A. 1998. Response of effluent-irrigated Eucalyptus grandis and Pinus radiata to salinity and vapor pressure deficits. Tree Physiology 18, 565–573.

Ngugi M.R., Hunt M.A., Doley D., Ryan P. and Dart P.J. 2003. Effects of soil water availability on water use efficiency of Eucalyptus cloeziana and Eucalyptus argophloia plants. Australian Journal of Botany 51, 159–166.

O'Grady A.P., Carter J.L. and Bruce J. 2011. Can we predict groundwater discharge from terrestrial ecosystems using eco-hydrological principals? Hydrology and Earth System Sciences Discussions 8, 8231–8253.

Passioura J.B. 1977. Grain yield, harvest index and water use of wheat. Journal of the Australian Institute of Agricultural Science 1, 117–120.

Passioura J. 2006. Increasing crop productivity when water is scarce—from breeding to field management. Agricultural Water Management 80, 176–196.

Passioura J.B. and Angus J.F. 2010. Improving productivity of crops in water-limited environments. Pp 37–75 in 'Advances in Agronomy Vol 106', ed. by Donald L. Sparks. Academic Press.

Penman H.L. 1949. The dependence of transpiration on weather and soil conditions. Journal of Soil Science 1, 74–89.

Priestley C.H.B. and Taylor R.J. 1972. On the assessment of surface heat flux and evaporation using large scale parameters. Monthly Weather Review 100, 81–92.

Raison R.J. and Myers B.J. 1992. The Biology of Forest Growth experiment: linking water and nitrogen availability to the growth of Pinus radiata. Forest Ecology and Management 52, 279–308.

Rangan H., Kull C.A. and Alexander L. 2010. Forest plantations, water availability, and regional climate change: controversies surrounding Acacia mearnsii plantations in the upper Palnis Hills, southern India. Regional Environmental Change 10, 103–117.

Rebelo L-M., Johnston R., Karimi P. and McCornick P.G. 2014. Determining the dynamics of agricultural water use: cases from Asia and Africa. Journal of Contemporary Water Research & Education 153, 79.

Roberts J. and Rosier P.T.W. 1993. Physiological studies in young Eucalyptus stands in southern India and derived estimates of forest transpiration. Agricultural Water Management 24, 103–118.

Ryan M. G., Stape J.L., Binkley D., Fonseca S., Loos R., Takahashi E.N., Silva C.R., Hakamada R., Ferreira J.M., Lima A.M., Gava J.L., Leite F.P., Silva G., Andrade H. and Alves J.M. 2010. Factors controlling Eucalyptus productivity: how water availability and stand structure alter production and carbon allocation. Forest Ecology and Management 259, 1695–1703.

Saeki T. 1960. Interrelationships between leaf amount, light distribution, and total photosynthesis in a plant community. Botanical Magazine, Tokyo 73, 404–408.

Searson M.J., Thomas D.S., Montagu K.D. and Conroy J.P. 2004. Leaf water use efficiency differs between Eucalyptus seedlings from contrasting rainfall environments. Functional Plant Biology 31, 441–450.

Smakhtin V. 2001. Low flow hydrology, a review. Journal of Hydrology 240, 147–186.

Stape J.L., Binkley D. and Ryan M.G. 2004. Eucalyptus production and the supply, use and efficiency of use of water, light and nitrogen across a geographic gradient in Brazil. Forest Ecology and Management 193, 17–31.

Stape J.L., Binkley D. and Ryan M.G. 2008. Production and carbon allocation in a clonal Eucalyptus plantation with water and nutrient manipulations. Forest Ecology and Management 255(3–4), 920–930.

Stape J., Binkley D., Ryan M.G., Fonseca S., Loos R., Takahashi E.N., Silva C.R., Silva S., Hakamada R., Ferreira J.M., Lima A.M., Gava J.L., Leite F.P., Silva G., Andrade H.B. and Alves J.M. 2010. The Brazil Eucalyptus Potential Productivity Project: influence of water, nutrients and stand uniformity on wood production. Forest Ecology and Management 259, 1684–1694.

Tan Z., Zhang Y., Song Q., Liu W., Deng X., Tang J., Deng Y., Zhou W., Yang L., Yu G.R., Sun X.M. and Liang N. 2011. Rubber plantations act as water pumps in tropical China. Geophysical Research Letters 38, 1–3.

Teng J., Chiew F.H.S., Vaze J., Marvanek S. and Kirono D.G.C., 2012. Estimation of climate change impact on mean annual runoff across continental Australia using Budyko and Fu equations and hydrological models. Journal of Hydrometeorology 13, 1094–1106.

Tomar V.S. and O'Toole J.C. 1980. Water use in lowland rice cultivation in Asia: a review of evapotranspiration. Agricultural Water Management 3, 83–106.

van Dijk A. and Keenan R.J., 2007. Planted forests and water in perspective. Forest Ecology and Management 251, 1–9.

Vertessy R.A., Watson F.G.R. and O'Sullivan S.K. 2001. Factors determining relations between stand age and catchment water balance in mountain ash forests. Forest Ecology and Management 143 (1–3), 13–26.

Vertessy R.A., Zhang L. and Dawes W.R. 2003. Plantations, river flows and river salinity. Australian Forestry 66, 55–61.

Ward, P.R. Dunin F.X. and Micin S.F. 2002. Water use and root growth by annual and perennial pastures and subsequent crops in a phase rotation. Agricultural Water Management 53, 83–97.

Watanabe K., Yamamoto T., Yamada T., Sakuratani T., Nawata E., Noichana C., Sributta A. and Higuchi H. 2004. Changes in seasonal evapotranspiration, soil water content, and crop coefficients in sugarcane, cassava, and maize fields in Northeast Thailand. Agricultural Water Management 67, 133–143.

White D.A., Beadle C.L., Honeysett J.L. and Worledge D. 1994a. The effect of drought stress on height, diameter and leaf area index of Eucalyptus globulus and E. nitens. In 'Australian tree species research in China', ed. by A.G Brown. ACIAR Proceedings No. 48, 71–76. Australian Centre for International Agricultural Research: Canberra.

White D.A., Beadle C.L., Honeysett J.L. and Worledge D. 1994b. Stomatal conductance of Eucalyptus globulus and E. nitens in irrigated and rainfed plantations. In 'Australian tree species research in China', ed. by A.G Brown. ACIAR Proceedings No. 48, 56–63. Australian Centre for International Agricultural Research: Canberra.

White D.A., Beadle C.L. and Worledge D. 1996. Leaf water relations of Eucalyptus globulus ssp globulus and E. nitens: seasonal, drought and species effects. Tree Physiology 16, 469–476.

White D., Beadle C., Battaglia M., Benyon R., Dunin F. and Medhurst J. 2001. A physiological basis for management of water use by tree crops. Pp. 20–27 in 'Plantations, Farm Forestry and Water. Proceedings of a national workshop', ed. by E.K.S Nambiar and A.G. Brown. RIRDC Publication No. 01/20. Rural Industries Research and Development Corporation.

White D., Battaglia M., Bruce J., Benyon R., Beadle C., McGrath J., Kinal J., Crombie S. and Doody T. 2009a. Water-use efficient plantations—separating the wood from the leaves. Forest & Wood Products Australia Ltd Report. Forest & Wood Products Australia: Canberra, Australia.

White D.A., Crombie D.S., Kinal J., Battaglia M., McGrath J.F., Mendharn D.S. and Walker S.N. 2009b. Managing productivity and drought risk in Eucalyptus globulus plantations in south-western Australia. Forest Ecology and Management 259, 33–44.

White D.A., Battaglia M., Mendham D.S., Crombie D.S., Kinal J. and McGrath J.F. 2010. Observed and modelled leaf area index in Eucalyptus globulus plantations: tests of optimality and equilibrium hypotheses. Tree Physiology 30, 831–844.

White D., McGrath J., Ryan M., Battaglia M., Mendham D., Kinal J., Downes G.M., Crombie D. and Hunt M. 2014. Managing for water-use efficient wood production in Eucalyptus globulus plantations. Forest Ecology and Management 331, 272–280.

Whitehead D. and Beadle C. 2004. Physiological regulation of productivity and water use in Eucalyptus: a review. Forest Ecology and Management 193, 113–140.

Wongprom J. 2012. Water use and water use efficiency of four eucalypt clones planted on paddy bunds in Chachoengsao Province. Master Thesis from the Forestry Department. Kasetsart University, Bangkok, Thailand.

Wongprom J., Cachrinrat C. and Srigongpan R., 2012. Water use and water use efficiency of eucalypt intercropped with cassava in Watthana Nakorn District, Sa Kaoe Province. Thailand Journal of Forestry 31(1), 20–25.

Zhang L., Dawes W.R. and Walker G.R. 2001. The response of mean annual evapotranspiration to vegetation changes at the catchment scale. Water Resources Research 37(3),701–708.

Zhang L., Hickel K., Dawes W.R., Chiew F.H.S., Western A.W. and Briggs, P.R. 2004. A rational function approach for estimating mean annual evapotranspiration. Water Resources Research 40 (2).

Zhang Y. and Chiew F.H.S. 2012. Estimation of mean annual runoff across Southeast Australia by incorporating vegetation types into Budyko framework. Australian Journal of Water Resources 15, 109.

Zhou G.Y., Morris J.D., Yan J.H., Yu Z.Y. and Peng S.L. 2002. Hydrological impacts of reafforestation with eucalypts and indigenous species: a case study in southern China. Forest Ecology and Management 31, 209–222.

Appendix 1. Methods used to estimate plantation water use at Qipo Forest Farm, Nanning

The components of plantation water use at Qipo Forest Farm, Nanning, Guangxi Province, China were estimated as follows.

1. Transpiration

   Sap flow sensors were installed in six trees. These trees were selected to cover the range of tree size in the stand. The installation in each tree consisted of a probe with a line heater and two sensor probes, each of which housed two thermocouples. Sap flux density of the individual trees was calculated using the heat ratio method, as described in Brooksbank et al. (2011)

   Stand sapwood area was calculated using allometric relationships developed in the same stand and the diameter of 30 trees in a plot that included the measurement trees. Stand transpiration was then calculated as the product of average sap flux density and stand sapwood area.

2. Interception

   Canopy interception was calculated as the difference between rainfall measured inside and outside the plantation. For two months where rainfall data inside the plantation were unavailable, interception was calculated using a linear relationship between rainfall and interception developed using data for the other 10 months of the year.

3. Soil water content

   The soil profile was 2 m deep and the total plant-available soil water was calculated as the integral of the product of the volumetric soil water fraction measured at 5 cm, 10 cm and 20 cm below ground and soil depth for each sensor.

4. Understorey water use

   Understorey water use incudes interception by weeds, weed transpiration and soil evaporation. It was assumed that the weed layer was accessing 1 m of soil. Water use of the understorey was calculated as equilibrium evaporation which is approximately 0.18 times net radiation. The amount of radiation absorbed by the understorey (net radiation) was assumed to be the same proportion of total radiation measured below the canopy as was observed above the canopy.

Appendix 2. A description of the water-balance model that is used in the water-balance calculator

The following is a description of the simple tool that calculates plantation water use the simple model described by Equation 7 (repeated below). This tool was used to estimate evapotranspiration by plantations of *Eucalyptus* in South-East Asia in Section 4.

1. The model is initialised at the end of the wet season. The soil water deficit is set to zero so that the relative plant-available soil water (w) is 1.00.
2. The crop factor for that month is calculated as a function of the relative plant-available soil water at the start of the month, i.e.

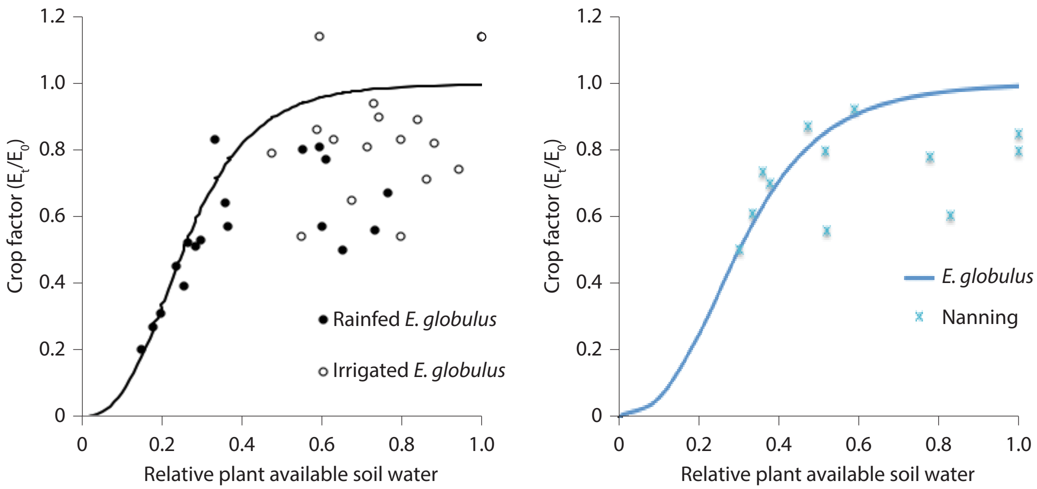
   $$k = \min\left[0.9, \frac{w^2 e^{a_w w}}{w_0 e^{a_w w_0} + w^2 e^{a_w w}}\right]$$

   where k is the crop factor and w_0 is the value of w for which k is 0.5 and a_w is the slope of the linear portion of the relationship between k and w. For *Eucalyptus globulus* (Battaglia and Sands 1997) and *E. urophylla* × *grandis* w_0 is 0.3 and a_w is 3.5.
3. Evapotranspiration for the month is then given by the following equation.

   $E_t = kE_0$
4. The water balance at the end (wf) of the month is calculated as:

   $w_f = \max(0, w_i - E_t + P)$

   where w_i is the water content (mm) of the soil at the start of the month and P is rainfall.
5. Step 2 is repeated iteratively for each month using w at the end of the preceding month to calculate the crop factor and evapotranspiration.



ACIAR

Research that works for developing countries and Australia

aciar.gov.au