

Development of sustainable forestry plantations in China: a review

John W. Turnbull

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Australian Government

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Foreword

The forestry sector in China is a major contributor to economic growth. The development of fast-growing, high-yielding plantations for wood production has made a significant contribution to this sector, especially over the past 20–30 years.

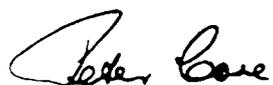
Research into fast-growing, high-yielding plantation species, many of which are eucalypts from Australia, has been an important part of the Australian Centre for International Agricultural Research (ACIAR) program in China since the Centre's inception.

Three impact assessment studies into this research activity have been commissioned by ACIAR during the past 15 years and, in each case, as more concrete evidence has become available, it has been shown that the returns on investment have been extremely high.

For development to be as impressive as this aspect of Chinese forestry has been, it was crucial for many individuals and organisations to work together. Attribution of the benefits from a successful research activity is always difficult, and can be a sensitive issue. While the authors of all ACIAR Impact Assessment Series reports are mindful of this, there is rarely sufficient time to provide a full and detailed description and analysis of the whole activity and all contributions.

ACIAR felt the need to more fully document the story of Chinese forestry development, because of its socio-economic significance. Doing so also helps illustrate how collaboration and coordination of a range of research and development activities are required for success.

We believe that the story Dr John Turnbull relates in this interesting report is important and will be useful to others undertaking large, complex, research and development activities. We thank John for his account, and also the many people who collaborated with him to ensure the details are clear and accurate.



Peter Core
Director
ACIAR

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Abbreviations

ACIAR	Australian Centre for International Agricultural Research	GIFDCP	Guangxi Integrated Forestry Development and Conservation Project
AIDAB	Australian International Development Assistance Bureau (now AusAID)	ITTO	International Tropical Timber Organization
APP	Asia Pulp and Paper	MDF	medium-density fibreboard
AusAID	Australian Agency for International Development	MOFERT	Ministry of Foreign Economic Relations and Trade
CAF	Chinese Academy of Forestry	NAP	National Afforestation Project
CERC	China Eucalypt Research Centre	R&D	research and development
CIFOR	Center for International Forestry Research	RITF	Research Institute of Tropical Forestry
CPC	Communist Party of China	SFA	State Forest Administration
FRDPP	Forest Resource Development and Protection Project		

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Summary

China is one of the world's leading wood-consuming countries and globally is ranked first in log imports. Wood consumption per capita in China is much lower than the world average but, with a population of 1.3 billion, the overall demand for forest products is massive. There has been an imbalance between supply and demand for wood from its forests for many years and this has been exacerbated as the Chinese economy has expanded. Paper consumption has risen, there has been growth in house construction, and the furniture industry has expanded. Fast-growing plantations of eucalypts and other species are being established to satisfy some of this demand.

Eucalypts have been planted in southern China for more than 100 years and have demonstrated that they consistently outperform other species on most sites. It was not until the People's Republic of China was founded in 1949 that planting eucalypts on a large scale for wood products was advocated, although initially most planting was to establish protection forests. Most of these mass-afforestation activities did not include post-planting tending and resulted in vast areas of poorly stocked plantations. Subsequent plantations aimed to produce round timbers for the mining industries. *Eucalyptus exserta*, *E. globulus* and *Corymbia citriodora*, from unimproved local seed sources, were the main species, fertilisers were rarely applied, and growth rates were 6–10 m³/ha/year or less.

Government policies have had a major influence on plantation development, to what extent they are profitable, and whether sufficient wood can be produced economically to meet the requirements of the wood-based industries. Implementation of 1978 policy decisions on land reform and opening of the country to the outside world had a positive impact on eucalypt plantation development. National forest

research was given greater priority, and active eucalypt research programs were initiated by the Chinese Academy of Forestry through the Research Institute of Tropical Forestry and, later, by the China Eucalypt Research Centre. Provincial institutes, such as the Guangxi Forest Research Institute, also conducted eucalypt research. International collaboration was encouraged and cooperative projects supported by the Australian Agency for International Development and the Australian Centre for International Agricultural Research demonstrated the potential to increase productivity of plantations by using selected species, modern nursery techniques and efficient plantation management practices. Over the past 25 years, advances in tree breeding and management practices have doubled the average productivity of eucalypt plantations in many areas. Yields of 20–30 m³/ha/year from clonal plantations are attainable where environmental conditions are favourable and good management practices are applied.

The Ministry of Forestry introduced a new policy promoting 'fast-growing, high-yielding' plantations for wood production in 1985 and, by 1990, forest research had provided a suite of new technologies to replace outdated and inefficient plantation practices. Eucalypt plantations became commercially attractive for investors and played an increasingly important role in forestry in southern China. Government policies in the early 1990s encouraged provinces, prefectures and counties to facilitate development of eucalypt plantations, chipping factories and pulp mills to stimulate export trade. Strategies were developed to expand eucalypt plantations in each province. About 100,000 hectares of eucalypts have been established with loans from the World Bank.

The national government has supported establishment of industries based on eucalypt plantations through a variety of financial and tax incentives designed to encourage foreign investment in the wood fibre, pulp, paper, and wood-processing sectors. There has been a series of policy initiatives to encourage plantation development and wood marketing. These policies have encouraged the private sector to become increasingly involved. In recent years, non-state commercial forestry enterprises (including joint ventures) and farmers have established most eucalypt plantations. Major paper producers are aiming to secure their pulp supplies by establishing large-scale eucalypt plantations and purchasing wood from private growers. Guangdong, Guangxi, Hainan and Yunnan provinces have become the focus of this development. More extensive planting of cold-tolerant eucalypts in Fujian, Hunan, northern Guangxi, Sichuan and possibly Jiangxi is likely to boost future supplies of wood fibre. There are now about 1.5 million hectares of eucalypts and about 90,000 hectares are planted annually. In addition, there are over 1.8 billion trees growing in 'four-side' plantings (equivalent to an additional 350,000 hectares), mainly in Yunnan and Sichuan. Although there has been very active establishment of eucalypt plantations in southern China by companies planning integrated forest-pulp-paper industries, they face obstacles in their efforts to secure sufficient plantation land and it is likely that they will remain partially reliant on imported woodchips for several years.

Domestication of eucalypts in China has progressively resulted in higher wood yields and shorter rotation intervals. Research contributing to the domestication process included species/provenance selection, tree breeding, nursery practices, silvicultural practices (e.g. site preparation and planting, fertilisers, mycorrhizas) and wood quality. In general terms, yields have doubled and the rotation period has shortened from 10 years to 4–7 years. Seed orchards now produce improved, high-quality seed and, associated with this, has been the application of vegetative propagation techniques to produce clones. Trials in the warmer coastal regions of Guangdong, Guangxi and Hainan demonstrated the superiority of species such as *E. urophylla* and *E. tereticornis* and clones of the hybrid *E. urophylla* × *E. grandis* over the local land races of *E. exserta* and *C. citriodora*. Selection of cold-tolerant species and provenances has greatly extended the

geographical range over which commercial eucalypt plantations can be potentially profitably grown in south-central China, but there is scope for further evaluation of some species. Most plantations in warmer areas are now based upon selected clones of the new introductions. Elsewhere, seedlings are used because the species planted, e.g. *E. globulus*, *E. maidenii*, *E. smithii* and *E. dunnii*, are difficult to propagate as rooted cuttings, or improved clones have not been adequately developed.

Soils on many sites planted with eucalypts in south China are acidic, highly leached, deeply weathered and often degraded by erosion. They are low in organic matter, so nitrogen is limited, and deficient in available phosphorus, potassium and some micronutrients such as boron. The earliest eucalypt plantations were established with little or no fertiliser. Research has confirmed the benefits of fertiliser application on the early growth of eucalypts, and helped change perceptions and practice. The benefits of species selection and breeding cannot be achieved without the application of fertilisers.

Support for continuing research to further increase the productivity of eucalypt plantations is essential to reduce the high costs of delivered wood. High costs limit the competitiveness of Chinese wood growers, who must compete with pulp imports from more efficient producer countries.

There are questions about the sustainability of fast-growing, short-rotation, eucalypt plantations in southern China. At the landscape level, there is little evidence that the plantations will have significant negative effects on biodiversity. Similarly, water use by eucalypt plantations does not appear to be deleterious for local water supplies in areas where rainfall and atmospheric humidity are relatively high but, in drier areas (<1200 mm/year rainfall), impacts on water supplies should be monitored, and silvicultural practices such as tree spacing and thinning modified if necessary to reduce water use. Nutrient depletion and/or erosion of relatively fragile soils are of concern, but can be managed if appropriate silvicultural practices, such as minimal cultivation, organic matter retention and fertilisation, are applied consistently. A greater risk to sustainability is the potential for serious damage by pests and diseases to monoclonal plantations lacking genetic diversity.

Eucalypts are providing new sources of income for individual farmers and collectives with the necessary management skills, access to capital and land to grow plantations. Employment opportunities being created in some areas will assist some of the poorest local households, or poor migrants from other provinces, to secure off-farm income. There are also opportunities for farmers to derive income by leasing their land to wood-based industries for plantation development. The socioeconomic impacts of eucalypt plantations are generally positive, but although plantation development has contributed significantly to poverty alleviation in some areas, it is probable that greater benefits accrue to higher income groups.

Introduction

Domestication of eucalypts and changes in government policies to encourage the production of wood for industrial use have been critical to the development of an extensive area of commercial eucalypt plantations in southern China. With more than 1.5 million ha of eucalypt plantations, and more planned, eucalypts are now a significant part of the rural landscape in southern China. They are having environmental, social and economic impacts, and these may be positive or negative depending on how the plantations are managed. It is critical that strategies are devised and appropriate practices implemented to ensure the sustainability of these plantations and the best possible outcomes for the Chinese people, their economy and the environment.

Since its establishment in 1949, the People's Republic of China has moved from a planned, centralised economy, through a series of reforms, to a socialist market-economy system. Implementation of the many policy changes involved has resulted in unprecedented economic growth. As the economy has grown, new forest policies have had a major impact on the forestry and forest industries sector of the economy and have directly affected development of eucalypt plantations and associated industries.

Development of commercial eucalypt plantations to produce wood and non-wood products has hinged on the domestication of *Eucalyptus* species. Domesticating a tree species is the process of transforming it from its wild, uncultivated state into genetically changed forms that are grown in plantations to produce higher yields

and better-quality wood and non-wood products. This is usually achieved by successive generations of selection and mating. The effective capture, enhancement and transfer of genetic gains from breeding programs and plantation development depends on the breeding strategy employed, the method of delivery of the gains to the plantation (including the use of clones) and overall plantation management (MacRae 2003).

The objective of this review is to trace the progress of the introduction and domestication of eucalypts in China and development of the eucalypt plantations in the context of the use of China's native forest resources and the evolution of government policies. The review also considers the sustainability of current eucalypt plantations, including their environmental and socio-economic impacts. Contributions of national and international organisations to the domestication process are described. A review of past developments provides a basis for identifying emerging problems in sustaining and further developing the eucalypt plantations and associated industries.

Background

Overview of China's forest resources

China is poor in forest resources and these resources are under great pressure due to the large and increasing population, economic reforms and the booming Chinese economy. It is important to understand the state of the country's forest resources and their contribution to domestic wood supply when considering the role of eucalypts in current and future plantations.

A major problem in assessing the capacity of forest resources in China to meet domestic wood demands is that the statistics are frequently conflicting and care must be taken to distinguish between the various categories of 'forest land' that provide China's industrial wood. Not all land categorised as 'forest land' is available for wood supply as some of it is protected, other areas are inaccessible for economic timber extraction, and some areas may have no trees on them. Hence, total forest area is a poor measure of 'timber forest' available for wood supply. The total forest area is about 197 million ha (FAO 2005), which is equivalent to about 0.15 ha per capita, significantly below the global average of about 0.75 ha per capita. A more realistic, but relatively optimistic, estimate of the effective timber forest estate is about 61 million ha, including plantations for industrial wood production (Bull and Nilsson 2004).

Primary and secondary natural forests account for 84% of forest area and most of the standing wood volume (FAO 2005). These forests are located mainly in the north-east and south-west of China. Accessible areas have already been heavily logged. Much of the remaining hardwood resource has been unavailable for timber production since 1998–2000, when the National Forest Protection Program introduced logging bans in the upper catchments of the Changjiang (Yangtze)

and Yellow rivers, and reduced logging in state-owned forests. In many places, the bans also extended to collective forests. Farmers are not allowed to harvest wood from their forests and sell it in the market, but the government has failed to adequately compensate collective forest owners for losing these rights (Miao and West 2004; White et al. 2006). The ban on commercial wood logging from natural forests was also extended to planted forests, and included a ban on harvesting for non-commercial use and tight control over fuelwood harvesting (Liu Dachang, The Nature Conservancy, pers. comm. 2006).

There are many demands on forest lands apart from the production of industrial forest products. The supply of non-timber forest products and fuelwood is very important throughout China, and demands for these products must be increasingly met from plantations as the natural forest resource shrinks. Forests also provide essential services such as watershed protection and biodiversity conservation. Analysis of these demands has highlighted the significant challenges facing China in managing its forest resources (Bull and Nilsson 2004).

There is great variation in reported statistics for plantation area, and considerable uncertainty about the condition and potential products of this resource. Towards the end of the 1990s, it was estimated that there were about 17 million ha of productive plantation. Jaakko Pöyry (2001) (cited in Bull and Nilsson (2004)) estimated that only about 5 million ha were planted to 'fast-growing' trees. 'Fast-growing' is used loosely in relation to eucalypts in China and growth is often less than the 15 m³/ha/year used by the Center for International Forestry Research (CIFOR) to define 'fast-wood' plantations (Cossalter and Pye-Smith 2003). In the 'Global Forest Resource Assessment 2005', China reported a total of 54.6 million ha of plantation, of which about 28.5 million ha were for wood production

(FAO 2005). As in the 1990s, it is unlikely that more than one-third of these are fast growing. The main fast-growing species in plantations are *Eucalyptus* spp., *Populus* spp., *Pinus massoniana* and *Cunninghamia lanceolata*, and official estimates of mean annual increment range from 9–18 m³/ha/year for *Eucalyptus* spp. to 3–8 m³/ha/year for *Pinus massoniana*, with *Populus* spp. and *Cunninghamia lanceolata* intermediate between them (Jaakko Pöyry 2001; cited in Bull and Nilsson (2004)). Actual growth rates may be much lower than these estimates (Bull and Nilsson 2004).

While the area of plantations has almost doubled since 1990, the area of mature natural forest has been rapidly shrinking, and the standing volume of timber has decreased significantly (FAO 2005). Estimates of the total wood volume in timber forests are in the range 6.6–7.2 billion (×10⁹) m³, of which an estimated 2.2–4.5 billion m³ is available for wood supply (Bull and Nilsson 2004). Productivity of natural forests in the public sector is constrained by factors including over-harvesting and illegal logging, forests that are either relatively young or low in productivity, a system of state-owned enterprises that has to combine public land management with product processing and marketing, and a lack of clarity over the ownership and objectives of public forest lands (White et al. 2006). Fuelwood extraction from forests also shows no signs of falling, and many rural households still depend on forests for fuel.

In 2003, the consumption of industrial wood was estimated in FAO statistics as 247 million m³, of which 106 million m³ was imported. With the poor productivity of most plantations and decreasing yields from natural forests, the forest resources in China will continue to be insufficient to meet the rapidly growing consumption demands in the next 20 years. Although the deficit will have to be made up from imports, the plantation sector will continue to be critical in complementing wood supply from natural forests. To this end, the national government is promoting development of 13.3 million ha of fast-growing, high-yielding, plantations between 2001 and 2015. It is also encouraging companies to integrate pulp and paper facilities with plantations by granting loan-interest subsidies to enterprises investing in fast-growing, commercial plantations.

Trends in consumption and wood processing

China has become one of the leading wood-consuming countries in the world in recent years, as a result of its booming economy. Wood consumption per capita in China is only 0.12 m³, much lower than the world average but, since the country has a population of 1.3 billion, the overall demand for forest products is massive. China has been facing a worsening imbalance between supply and demand for wood from its forests for many years. As the Chinese economy has expanded and people have become wealthier, there has been a rapid increase in local demand for wood and wood fibre products. Growth in house construction—about 10 million new homes built annually, and rapid expansion of the furniture industry, have created a strong demand for forest products (Midgley 2005). China has now become a major importer of timber and the world's largest importer of logs (Sun et al. 2004).

The timber market in China has evolved since 1980, when all timber production and distribution was state planned. Nationally, a quota system has controlled commercial harvesting of logs since 1985. The State Forest Administration (SFA) determines annual harvest volume, total and by type of product, based on the volume cut the previous year and statistics from the national forest survey. The annual harvest quota comprises five product categories: commercial timber, timber for on-farm use, wood for sideline production such as fungi and mushroom cultivation, fuelwood, and wood for other uses. Volumes are not allowed to exceed the quota. The policy was incorporated into the revised Forestry Law of China in 1998, when full liberalisation of domestic timber trade began and, despite liberalisation of the market, the state still issues logging and transport permits. This control has been a serious disincentive for small-scale forest growers (Cai et al. 2003; White et al. 2006). Liberalisation of the timber market has resulted in individual traders increasingly joining state-owned timber companies purchasing and distributing wood resources (Sun et al. 2004).

Total wood removals (i.e. industrial wood plus wood removed by local people for many uses plus fuelwood removals) from forests in China rose gradually from 1989 to 1994 and have since fallen each year, suggesting industrial wood supplies are under pressure (Table 1)

(FAO 2005). In 1989, imports of wood (processed timber and logs) were about 5 million m³ (Xu 2003) but, by 2004, log imports alone were 28 million m³ (16 million m³ softwood; 12 million m³ hardwood) (Midgley 2005).

China has an extensive wood-processing industry. In the early 1990s, there were 2,200 sawmills with a capacity of 23.6 million m³ and 1,100 panel-board factories with a capacity of 4.8 million m³, but capacity utilisation was low due to maintenance problems and shortages of wood. Most operations were small-scale and labour-intensive. In recent years, the Chinese Government has promoted more efficient integrated operations, including fibreboard and particleboard manufacture, to use smaller log sizes and sawmill residues. Production capacity of medium-density fibreboard (MDF) has grown from 650,000 m³ in 1995 to over 16.5 million m³ in 2004; and particleboard has doubled from less than 2 million m³ to over 6.4 million m³ (Midgley 2005). China has become the world's largest producer of MDF. Investment in China's furniture and plywood industries has significantly increased exports of furniture and plywood (Sun et al. 2004).

Sawn timber production has remained relatively low in the past 10 years, due to limited domestic supply of sawlogs, but log imports have increased rapidly. There is potential for larger eucalypt logs to be grown in plantations to yield sawn timber and plywood products but, so far, few eucalypt plantations have been established specifically for these products.

The Chinese pulp and paper industry has, in the past, had many problems, including small and outdated factories with inadequate chemical recovery systems and effluent disposal facilities. Non-wood raw materials, such as straw, made up about 70% of fibre used,

resulting in inferior products and pollution problems. Despite these problems, in 1994 China was the third-largest producer of pulp and paperboard in the world, with an annual output of 18 million tonnes.

The Chinese Government recognised the need to give high priority to modernisation of the pulp and paper industry and announced policies to expand the area of fast-growing, high-yielding plantations for pulpwood production, closed thousands of small pulp and paper factories that were using non-wood materials, and supported the development of large, efficient pulp mills using woodchips. It also aimed to increase the autonomy of existing enterprises and expand shareholding corporate structures to more enterprises. It encouraged expansion of the private sector, including emphasis on developing joint ventures to encourage technology transfer and management reform in forestry and wood processing.

These reforms have had an impact, although some planned pulp mills have yet to be built, and ambitious plantation-area goals have not been fully achieved. China is now the world's second-largest producer of paper and paperboard, and is expected to dominate global capacity expansion for most grades of paper (Midgley 2005). Annual per capita consumption in China has risen from 12 kg in 1994 to 37 kg in 2006, and is projected to reach 65 kg by 2010. The demand for wood pulp is expected to rise from about 9 million tonnes in 2003 to 15 million tonnes by 2010 and this will place considerable pressure on domestic wood supplies (He and Barr 2004). This has been highlighted by the withdrawal of the Finnish company UPM Kymmene from a joint venture pulp-mill project in 2004 due to failure to secure sufficient wood from eucalypt plantations in western Guangdong (Cossalter 2005).

Table 1. Wood removals from forests in China

Year	Industrial wood removal (million m ³)	Wood removed by local people (million m ³)	Fuelwood removal (million m ³)	Total (million m ³)
1989	58	36	65	158
1994	66	45	62	172
1998	60	45	54	159
2002	44	45	47	136

Source: FAO (2005)

China is now following the model of countries like Brazil and Chile in developing integrated plantation–pulp facilities to produce high-quality eucalypt pulp for a modern, local paper industry. Major paper producers are beginning to secure their pulp supplies by establishing large-scale plantations and purchasing wood from private growers. There are opportunities for farmers to derive income by supplying wood or leasing their land to paper companies. The extent to which these plantations will contribute to the pulp and paper sector will depend on whether or not sufficient land is available in appropriate locations, and the plantations can be managed to reach their full potential and produce wood at a competitive cost (Barr and Cossalter 2004).

China's policies and their effects on development of the forest plantation sector

Economic reform

After the establishment of the People's Republic of China in 1949, the country had a planned, centralised economy and a period of 'self reliance', with much-reduced contact with other countries. Following the death of Mao Zedong in 1976, there was a period of 'readjustment' in China and, in December 1978, the Third Plenary Session of the Communist Party of China (CPC) 11th Central Committee decided to shift the policy focus to 'socialist modernisation', and implement a strategic decision on reform and 'opening' to the outside world. The main thrust of the reform included fundamental changes leading to a new economic structure.

Reform began in the countryside, with implementation of the contracted household responsibility system linking remuneration to output, and the two-layer management system featuring the integration of centralisation and decentralisation. A planned commodity economic structure based on socialist public ownership was proposed in 1984 and, in 1992, the 14th National Congress of the CPC put forward the goal of China's economic reform as establishing a socialist, market-economy system. In 1997, the non-public ownership sector was recognised as an important component of China's socialist economy and, to stimulate production, changes in the application of technology and capital were encouraged. By 2000, much had been done to reform state-owned enterprises and other key institutions, and China's socialist, market-economy system

is currently being instituted. Implementation of these many policy changes China has resulted in unprecedented economic growth.

The policies that have brought about the economic reforms have radically changed socioeconomic circumstances in China. Any consideration of the effect of direct forest policies on forest development needs to recognise that general economic conditions such as macroeconomic growth and stability are also important factors (Zhang et al. 2003a). They have resulted in a sharp increase in demand for forest products and have affected forestry development through changes in land and forest ownership, afforestation and deforestation. These changes have had, in turn, implications for domestic wood supplies and the development of fast-growing plantations to meet the demands. Some of the effects are summarised below and have been treated in greater detail in reviews by Richardson (1990), Sun (1992), Yin (1994), Zhang (2003), Barr and Cossalter (2004), Liu et al. (2004) and Nilsson et al. (2004).

Land and forest ownership

Before 1949, a small minority of rural families owned most forested land, but there were some communal forests, especially in Yunnan, Sichuan and Guizhou, and state forests, mainly in north-east China. Although the new government began to reorganise rural society in line with its planned, centralised economy, in the early 1950s most trees and forests remained largely in

the private ownership of farmers, and most forestry activities were conducted individually. By the end of 1956, with the enforcement of collectivisation, private ownership of forests had ended and all rural lands were merged into cooperatives made up of hundreds of households (Miao and West 2004). These cooperatives were further amalgamated in 1958 and decision-making transferred to the communes (townships). Collective ownership brought about inefficiency and disincentives in the agricultural sector and the whole country fell into economic depression between 1959 and 1962.

In late 1978, China began agricultural reforms that included abolition of collective agriculture and the introduction of household-based agriculture. Use rights to agricultural lands were distributed to individual farm households, while the village collective remained the owner of land. Along with the transfer of land-use rights, households gained increased authority to make decisions about land use and management, and marketing.

Nationwide forestry reform in the early 1980s followed the pattern of the agricultural reform. The decentralisation was limited to collective lands. Collective ownership included the lands of administrative villages and village household groups, these previously being known as production brigades and production teams, respectively. Use rights to denuded or non-forested collective land were distributed to individual households as their 'family plots', in an attempt to encourage them to plant trees and develop plantations. Collectives retained ownership of the land, but farmer households owned any trees they planted on their land. At the same time, the collectives also 'allocated' existing collective forests to farmer households to manage. In this case, the collectives owned the forests but transferred responsibility for forest management to individual households. Income

from the forests was shared between the collectives and the managing households, under a wide range of terms agreed by both parties (Cai et al. 2003).

The tenure of forest resources is more complicated than land ownership. Trees and forests are variously owned by the state, collectives, privately, or a mixed ownership in the form of shareholding systems (Table 2). Since the 1980s, private and mixed ownership of trees has been separated from land ownership, based on a policy that 'whoever plants the tree owns it' (Liu 2001). The relative extent and importance of these categories of tree ownership varied widely from province to province. The state of tree and land tenure and their effect on farmers' revenue has directly influenced farmers' attitudes to engaging in forestry as part of their farming operations (He 1995). The evolution of tree tenure and wood marketing arrangements in non-state forests in southern China to 2003 is summarised in Table 3.

State timber forests are controlled by government agencies or enterprises. In addition, the railway, army, coalmines and other entities manage forests for their own use. There are over 4000 state-owned forest farms in China, mainly in northern provinces. 'Non-state forest' comprises trees or forests that are collectively, privately and jointly owned. Non-state forests are important, as they make up 60% of China's forest area and include about 60 million ha of timber forests. They are particularly important in the 12 provinces of southern China where eucalypts are planted, as they comprise up to 90% of the forest land in some of those provinces (Liu 2001). The ownership status of land is important today, as joint-venture companies developing eucalypt plantations must rent land from state forest farms or collectives, or the 'private land' of individual households. 'Private land' is land for which the household has been granted individual use rights by the village collective.

Table 2. Changes in ownership of China's forests

1950s to 1980s		2005	
State forests	45%	State forests	42%
Collective forests	55%	Collective forests	38%
		Household/private forests	20%

Source: Liu Dachang (pers. comm. 2006), based on Ministry of Forestry and State Forest Administration data

Tenure conditions for forest land and resources have not improved as quickly as they have in the agricultural sector, and forestry activities have been subject to tight government control by local forest authorities and government agencies. However, a directive by the CPC Central Committee and the State Council 'decisions regarding speeding up forestry development' launched a new round of decentralisation in collective forest resources in 2003. Full-scale, nationwide reforms are included in the Eleventh National Five-year Plan (2006–2010) and are being implemented.

Under the new policy, forests are classified as either 'ecological forests' or 'commercial/timber forests'. Tenure reform will be carried out in commercial forests, focusing on collective forests. The government will be the main manager of ecological forests. Collective

forests are being transferred to individual farmer households, in contrast to earlier reforms, when only non-forested lands were transferred. Land-use rights to these forests and tree ownership are distributed to farmer households for 30–70 years and trees on the land are also household property. This gives greater power to farmers, who can now make forest management decisions, sell and lease their land-use rights, sell their standing trees, and use their forest as shares in forestry enterprises or as collateral for bank loans. Farmers can sell their wood on the free market, and reduced taxes and fees will enable them to derive a better return from their forest land. High taxes have been a serious disincentive for tree planting and forest management, and have had negative social and environment effects (Liu 2003). The new policy is expected encourage farmers to invest more in plantation establishment

Table 3. Evolution of tree tenure and marketing systems in non-state forests in south China

Period	System	Ownership	Timber marketing
Before 1950	Historical	Bureaucrats, landlords, timber merchants and self-sustaining farmers	Free market
1950–1955	Land reform	All farmers, including self-sustaining farmers and former landlords	Free market
1956–1958	Socialist transformation and agricultural collectivisation	Collective ownership and production	Quotas and prices determined by the state
1958–1979	People's communes	Collective ownership and production	Quotas and prices determined by the state
1979–1983	Household-based agriculture (contract responsibility) and people's communes	Family forest plots (<i>ziliushan</i>); responsibility forest land (<i>zerenshan</i>); collective forest	Self-determined production: compulsory delivery system
1984–1999	Household-based agriculture	Family forest plots, responsibility forest land collective forest; shareholding system	Price controls lifted, but taxes and fees increased; government monopoly on procurement
1999–2005	Household-based agriculture and logging ban in natural forest in 17 provinces	As above, but encouragement of foreign investors to rent land for plantation development	No timber harvesting is allowed from collective and private plantations and natural forests. Reduced taxes and fees on harvested wood to stimulate investment; tariff reductions on imports of raw materials and processing machinery

Sources: based on Sun (1992) and Liu (2001)

and management, and will improve their livelihoods (SFA 2006). Overall, this reform should increase wood production, reduce rural poverty, and assist regional economic development.

The national harvesting quota and associated logging permits remain part of government policy and may discourage owners and managers of collective forests and household forests from establishing timber plantation forests, and so undermine the benefits of the new tenure reforms. The centrally approved quota is allocated through county forestry bureaus to the township level, and thence among villages. It is difficult for owners and managers of collective forests and especially household forests to obtain logging permits. Often the entire harvest quota for a township is allocated solely to forest farms and traders. In addition, the process of applying for a logging permit is time-consuming, and preparation of the relatively complex documentation may be beyond the capacity of some farmers (Liu Dachang, The Nature Conservancy, pers. comm. 2006).

Deforestation

Several Chinese Government policies have led to deforestation and forest degradation. Perhaps the most devastating was the 'Great Leap Forward' campaign. This policy was launched in 1958 to encourage industrialisation (with steel output as the major indicator) and self-sufficiency in grain. People were mobilised throughout China to make iron and steel using backyard furnaces and these consumed large quantities of fuelwood and charcoal. Forested land was cleared and cultivated to increase grain production. This countrywide campaign caused major deforestation and reduced the productivity of many of those forests that were not cleared.

Deforestation is often a consequence of a breakdown in the forest management system. This has happened in many places in China, especially during the 'Great Proletarian Cultural Revolution' and after the forest reform in the early 1980s. The Cultural Revolution started in 1966 and lasted until 1976. It paralysed almost the whole governance system from national to village level, and the abnormal political and

policy environment resulted in the breakdown of the management system of collective forests in many areas (Cai et al. 2003). Forest reform also led to a breakdown in governance in some places. In one village in Yunnan, for example, collective ownership of the eucalypt plantation established in the 1960s was retained after the reform, but no one was given authority to manage the plantation and consequently villagers cut down almost all the trees (Lai et al. 2003).

It is highly probable that frequent changes in forest tenure policy in China over the three decades to the early 1980s were responsible for the significant deforestation that occurred immediately after adoption of the household-based forest-management system. The root cause of the deforestation was a lack of farmer confidence in security of tenure, an attitude arising from experience in the period from the 1950s to the 1980s. Farmers were not convinced that the government's new policy would not be revoked and so they immediately harvested trees distributed to them to realise their value. The premature harvesting led to a huge loss of both natural forest and plantations. Despite these initial setbacks, the policy reforms reversed the decline in forest cover that had been occurring since the beginning of the communist state and there was an increase in forest cover between 1980 and 1993 (Rozelle et al. 2003).

Afforestation

In 1952, the Ministry of Forestry prepared a 'Directive on mass afforestation, cultivation of forests and protection of forests' that called for afforestation of hills and wasteland. This program seems to have aimed at directing peasant farmers to plant protection forest rather than state-supported production forests. In 1956, an ambitious target of 'planting 100 million hectares of barren lands and mountains within twelve years' was announced and emphasis was placed on economic crops (fruit trees etc.) and fast-growing tree species (Richardson 1966).

After collectivisation, farmers were left with few trees near their houses; afforestation was carried out by 'organising the masses' and management of existing forests was neglected (Yin 1994). There was virtually no private investment during this period of 'self-reliance',

and farmers usually did not participate in decision-making. Officials of communes and production brigades made most decisions about land use and management on the collectively managed lands. The collectives generally paid little attention to establishing timber plantations, and their efforts were considered merely a supplement to the state investments in forestry (Zhang 2003). Meanwhile, the central government established more state-run forest farms: by 1966, there were 3,300 of them, with about 80% controlled by county governments and the remainder by prefectural and provincial administrations (Yin 1994). These forest farms were generally more successful than those planted by communes, which received virtually no management (Richardson 1990). Many of the plantations established were located on poor sites, had unimproved planting stock, and were inadequately maintained. These factors contributed to poor survival, often as low as 10%, and slow growth. Table 4 shows the relative areas of different types of plantation forests established from 1949 to 1977.

Priority was placed on the quantity of new trees planted in the period up to 1985. Little attention was given to the quality of planting and subsequent plantation maintenance, so the productivity of the plantations was much lower than expected (Yin 1994). The Ministry of Forestry introduced a new policy in 1985, promoting 'fast-growing, high-yielding' plantations for timber production. This demonstrated a recognition by the policymakers that plantation productivity could be improved only by changing outdated and inefficient practices. The program aimed to establish plantations on better soils, use better-quality nursery stock, and provide improved management techniques (site preparation, stocking rates, fertiliser application, weeding and harvesting). Species with potential for rapid growth were identified; they included eucalypts.

The policy was only partially successful, with only about a quarter of the 17 million ha of plantations established in 1985–1995 classed as 'fast-growing, high-yielding'.

Afforestation in China was affected in several ways by the implementation of the 1978 policy decisions on reform and opening to the outside world. Internally, national and provincial forest research institutes began to function again, and forest researchers and plantation managers started to meet and exchange information. The Academy of Forest Science was re-established under the Ministry of Forestry in 1978, and this exerted considerable influence over the direction of forest research throughout the country (FAO 1982). The opening up of China to external influences facilitated the exchange of information and enabled cooperation to begin with bilateral and multilateral development assistance agencies with forestry interests. Cooperative projects undertaken with agencies in Australia and with the World Bank significantly accelerated the domestication and planting of eucalypts.

Bilateral cooperation with Australia began in the period 1980–1985. Exchange missions under the Australia–China Agricultural Exchange Scheme familiarised foresters from both countries with the other's forestry resources and practices, and fostered cooperation and exchange of seeds and information. The Dongmen State Forest Farm Eucalypt Afforestation Project (1981–1989) was established under the Australia–China Program of Technical Cooperation. It aimed to contribute to the national goal of increasing wood production, by demonstrating improved plantation practices for fast-growing species in south China. The Guangxi Department of Forestry and the Queensland Department of Forestry implemented the project on behalf of the Chinese Ministry of Foreign Economic Relations and Trade and

Table 4. Types of plantations established in China, 1949–1977

Plantation type	Percentage of total area planted
Timber plantation	67
Bamboo plantation	13
Economic tree crops	12
Shelterbelt and protective plantation	6
Fuelwood plantation	2

Source: FAO (1982)

the Australian International Development Assistance Bureau (AIDAB) (Carter et al. 1981a; Cameron et al. 1988).

In 1985, cooperation between the Australian Centre for International Agricultural Research (ACIAR) and the Chinese Academy of Forestry (CAF) was initiated with a collaborative research project 'Introduction and cultivation of Australian broadleaved trees in China' (1985–1993). This project aimed to test species of *Eucalyptus*, *Acacia* and *Casuarina* in tropical and subtropical regions of China. Scientists from the Australian CSIRO Division of Forestry and Forest Products¹ established a series of trials in Hainan, Guangdong, Fujian and Yunnan provinces in partnership with CAF's Research Institute of Tropical Forestry (RITF) (Guangzhou), the Research Institute of Forestry (Beijing), and provincial forest research institutes (Boland and Turnbull 1989). A major component of this project was testing of eucalypt species and provenances, complementing similar studies underway at Dongmen State Forest Farm in Guangxi. From 1985 to 2005, ACIAR supported a total of seven projects involving eucalypts, at a cost of A\$18 million (van Bueren 2004). Different Australian and Chinese partner organisations were involved in each project, depending on the research objectives, and each organisation invested substantial resources into the implementation of the projects.

China joined the International Monetary Fund (IMF) and the World Bank in 1979, and forestry projects were financed through the World Bank's affiliate, the International Development Association, which promotes economic development in the world's poorest countries. Its loans are interest-free and repayable over very long terms, with extended grace periods. In a series of projects to enhance forest productivity, improve resource use efficiency and build institutional capacity for sustainable forestry management, the World Bank helped China overcome its problems of limited forest resources and growing deforestation. With this funding, the Forest Development Project (1985–1990) to support afforestation on state forest farms in Heilongjiang, Sichuan and Guangdong provinces was approved. It included establishing 82,000 ha of plantations, of which 24,000 ha would be 'fast-growing plantations'. It also

provided for strengthening of research at four provincial research institutes and for development of extension services. In 1988, the Da Xing An Ling Forest Fire Rehabilitation Project to salvage wood from a massive fire and improve fire control was also funded. The National Afforestation Project (NAP) followed in 1990 and the Forest Resource Development and Protection Project (FRDPP) in 1996.

When the NAP was proposed, the Ministry of Forestry was aware from some of the bilateral assistance projects that prevailing methods in plantation forestry needed to be improved, and that it could no longer rely on state forest farms to meet the country's serious deficiency in wood products. The project was implemented between 1990 and 1997 to finance afforestation, research and planting material activities and institutional strengthening in 16 provinces. A key objective was to improve the quality of forest plantations through use of superior planting stock. Its components included: (i) plantation establishment of 675,500 ha of coniferous and 309,500 ha of broadleaved tree (including eucalypts) plantations in 16 provinces; (ii) establishment of research working groups; and (iii) improvement of planting material and seed-production areas. A particular feature of NAP was the emphasis on involving collective forest farms (50% of planting area), share-holding forest farms (36%) and individual households (5%), rather than state forest farms alone that were used exclusively in the earlier Forest Development Project.

Complementing and extending the NAP, the FRDPP (1996–2000) aimed to expand the supply of commercial timber and pulpwood by establishing 620,000 ha of intensively managed plantations, including about 37,000 ha (6%) of eucalypts. In the 1990s, over 200,000 ha of eucalypt plantations were established using World Bank loans (Qi 2003). Extension within these projects was in the form of technical publications and training courses at central, provincial and county levels. The lack of a clearly defined extension mechanism with appropriate incentives had previously hampered the application of new technologies in plantations. In 2002, the China forestry program was the largest in the World Bank, and the largest forestry investment by any donor in any one country, with loans, grants and credits of US\$804 million (World Bank 2002). Support is continuing through the World Bank/Global Environment Facility 'Guangxi Integrated Forestry Development and Conservation Project' (GIFDCP).

1 The name and constitution of CSIRO cooperators changed several times in the period reviewed.

Several joint venture pulp and paper projects have started establishing plantations since 1997, but China will still need large quantities of wood pulp to satisfy its future paper and paperboard needs. Imports will be substantial and, to reduce the outflow of hard currency and dependence on other countries, the SFA has implemented plans to develop a commercial wood supply to support domestic forest-product industries, especially for new wood pulp capacity. China's Tenth Five-Year Development Plan (2001–2005) set short-term targets to triple domestic wood pulp capacity, and prioritised the expansion of integrated fast-growing pulpwood plantations, wood pulp and high-grade paper production. In 2003, the Central Committee and State Council promulgated a new government forest policy, 'Resolution on Accelerating Forest Development', introducing a series of aggressive development policies to achieve their targets (Barr and Cossalter 2004). These policies aim to reduce China's dependence on imported wood fibre, paper, and processed wood products by:

- developing fast-growing, high-yielding plantations
- reducing high taxes and fees on plantations, so as to stimulate investment
- reducing tariffs on imports of raw materials and processing machinery
- protecting China's forestry base
- encouraging foreign investment in the wood fibre, pulp, paper, and wood-processing sectors through a variety of financial and tax incentives.

Of the overall target to plant 13.3 million ha between 2001 and 2015, 2.5 million ha is to produce large-diameter timber, 5.0 million ha is to provide materials for solid wood products, and 5.8 million ha is for pulpwood. Eucalypts will form a significant part of a proposed 2.7 million ha of fast-growing, high-yielding plantations committed to pulpwood production in the south-coastal and middle/lower Changjiang (Yangtze) regions (Barr and Cossalter 2004).

Historical development of Chinese eucalypt plantations

Why plant eucalypts in China?

Eucalypt is the common name for species of two genera, *Eucalyptus* and *Corymbia*, that dominate Australia's natural forests and woodlands, and extend from temperate latitudes (42°S) in Tasmania to the tropics (11°S) in Queensland. Beyond Australia, small areas of natural eucalypt forests occur in tropical Indonesia, Papua New Guinea and the Philippines. Within this vast geographic range there is great ecological variability. Eucalypts are found in places with high rainfall but also in semiarid areas and along watercourses in arid deserts where rainfall is minimal and erratic. They fringe the coastal beaches in many places, yet also extend to an altitude of almost 3,000 m in the mountains of East Timor. In Tasmania, the varnished gum, *E. vernicosa*, is a sprawling shrub, while not far away in the Florentine Valley the giant mountain ash (*E. regnans*) is the tallest broadleaved species in the world and one of several species that can exceed 70 m in height. The genetic diversity of eucalypts is great: about 900 species have been described and many species exhibit very substantial intraspecific genetic variation.

Eucalypts have been grown successfully in the tropical, subtropical and warm-temperate regions of the world and show great adaptability in a wide range of environmental conditions, from humid-tropical lowlands to cool-temperate highlands. They have been planted as exotics for over 150 years and, in recent years, the rate of planting for industrial wood production has accelerated. The estimated area of planted eucalypts was 700,000 ha in 1955, 4 million ha in 1979 (FAO 1979),

and 16 million ha in 2005 (UNDP 2006). Relatively few *Eucalyptus* species are grown commercially. The five most extensively planted species are *E. grandis*, *E. camaldulensis*, *E. tereticornis*, *E. globulus* and *E. urophylla*. Clonal plantations, often using selected hybrid clones, are being established more frequently (Eldridge et al. 1993; Evans and Turnbull 2004).

A little over 100 years ago, eucalypts were introduced into southern China for ornamental use as individual specimen trees in gardens and parks, or planted on a small scale for screening along roads and railways, and around villages. From this local experience and reports from other countries, it was evident that eucalypts had the potential to provide many benefits very quickly, including industrial wood, poles and posts, fuelwood, timber for household use, nectar for honey production, essential oils, tannins and many other products.

Eucalypts were among the species used for plantations in the 1950s, when China's demand for wood products for domestic and industrial use exceeded the supply from natural forests. In 1985, eucalypts were identified by the Ministry of Forestry as species suitable for 'fast-growing, high-yielding' plantations for timber production. They were considered best adapted to southern China because of a number of key features that have also made them successful exotics around the world. Intolerance of extreme cold limits their use in northern areas. Some eucalypts characteristically grow very rapidly and straight, features often lacking in indigenous species. Fast growth means they can be managed on short rotations and can also result in quick canopy closure and, consequently, reduced weeding costs. As forestry is a relatively long-term activity, anything

that reduces costs early in the rotation, or shortens the rotation, helps to make the enterprise more profitable. Straight stems are relatively easy and economic to harvest and process, and are essential when poles or sawn timber are the desired product.

Eucalypts have evolved on a continent with infertile soils and highly variable rainfall, and have physiological characteristics that reflect these conditions. They usually consume less nutrients and water than indigenous species for production of the same amount of biomass (Davidson 1996). Most species are also relatively drought tolerant and have mechanisms that help the crown recover rapidly after damage by drought or fire. This wide adaptability to soils and climates means a species of eucalypt can usually be grown in large plantations covering a variety of soils and microclimates. At the same time, like all crops, they do place demands on their environment, so informed management is essential for best results.

In general, eucalypts have small seeds that are easily stored for long periods, and this facilitates their distribution to growers. They are easy to grow from seed, and most species coppice freely. Coppicing is a simple and reliable system for regenerating a tree crop that is cheaper and requires less expertise than use of seed or cuttings. Initial growth of coppice is faster in the early stages, and so it is ideal for plantations grown for fuelwood or pulpwood (Turnbull and Booth 2002). Techniques have been developed to efficiently propagate species and hybrids vegetatively by cuttings, so enabling quick capture of genetic gains from selection and breeding programs.

When eucalypts are grown in a new area in the absence of their coevolved parasites they are usually healthy and grow vigorously. This is the case for most exotic eucalypt plantations, but there is evidence, especially from the humid tropics and subtropics, that eventually they suffer attacks from non-specialist parasites. Careful species-site matching, and attention to integrated pest-management practices, will minimise such problems. The foliage of many eucalypts is not palatable to browsing animals, and this can be an advantage where they are used in farm forestry in association with livestock.

Apart from these silvicultural benefits, eucalypts can produce a wide range of wood and non-wood products, and environmental services. Wood products include construction timbers, furniture, farming tools, trans-

mission poles, railroad sleepers, fuelwood, charcoal, honey, rayon, fibreboard and plywood. Eucalypts are a preferred fibre source for a number of different wood pulps for the paper industry. An impressive range of non-wood products has been produced for many years (Song 1992), and China is the world's largest producer of essential oils from eucalypts (Chen 2002a).

Eucalypts have attracted more criticism by environmentalists than most species used in plantation forestry. Their main concerns are (i) excessive water use and depression of growth of food crops grown nearby, (ii) suppression of ground vegetation and the consequent unsuitability for soil erosion control and (iii) generally poor wildlife value (Evans and Turnbull 2004). While there is some substance to these concerns, each site to be planted must be assessed and a decision made on the relative advantages and disadvantages of growing a eucalypt crop on it. Unlike many exotic species, there are few places in the world where eucalypts have become weeds and threatened local biodiversity through invasion of natural ecosystems.

Companies usually plant eucalypts with the objective of obtaining a single product, such as pulpwood, as profitably as possible. On the other hand, farmers often select trees for planting that provide not only profitable and readily marketed products, such as wood products and non-wood products, but also environmental services such as shade and shelter. The use of trees as a living bank account, to be harvested when there is a need for cash, is widespread. Fast-growing species that are disease-free and easily managed are usually preferred by farmers because they give an early return on the capital invested and do not divert them from other activities. Some eucalypts meet these criteria and are popular with farmers in many parts of the world including China (Turnbull and Booth 2002). The main reason some Chinese farmers choose to plant *E. globulus* in Yunnan province is the quick cash return they get from harvesting leaves for cineole oil production, while branches and litter for fuel may be valued secondary products.

In global forestry, eucalypts have very often emerged as the best option in the difficult task of selecting a tree species to match the site conditions and to produce the desired end products economically. Consequently, eucalypts are now used in almost half of all planted forests in the tropics. The choice of eucalypts for

planting in southern China has been based upon many years of careful observation and scientific research that have demonstrated that they consistently outperform other species on most sites. Ensuring that large plantations of fast-growing eucalypts continue to be profitable and have positive social and environmental outcomes is a challenge for plantation managers in China. The sustainability of eucalypt plantations in China is discussed in a later section.

Pre-1949 introductions and planting

There has been a claim that, in pre-history, eucalypts were growing on what is now the Western Sichuan Plateau. Fossils found by the Academia Sinica in a late-Eocene formation, have been named *Eucalyptus reluensis* (Qi 2003; Chen et al. 2006). This precedes fossil evidence for eucalypts in Australia, found in the succeeding Oligocene epoch. Despite the reported fossil record, it is certain that today there are no endemic eucalypts growing in China.

The date of the first introductions of eucalypts to China is not known with certainty, but it may have been as early as 1874 (Wang et al. 1994a). Qi (1990, 2003) suggests eucalypts were introduced by 1890. In 1894, blue gums (*E. globulus*) were growing in the grounds of the French legation in Yunnan (Morrison 1895). Early introductions of *E. globulus* in Yunnan have grown to 50 m tall and over 160 cm diameter at breast height (Chen 2002a). An old and very large specimen of *E. globulus* is growing in the grounds of the Golden Temple in Kunming (Figure 1a). Eucalypts were also planted in Guangdong, Guangxi, Hainan, Fujian, Zhejiang, Jiangxi and Sichuan provinces at an early date (Qi 2003), but were probably not introduced into Hunan until 1926 (Lin et al. 2003). These early introductions included *E. tereticornis*, *E. camaldulensis* and *E. robusta*.

A hundred years ago eucalypts were usually introduced for ornamental use as individual specimen trees in gardens and parks (Figure 1b), or planted on a small scale for screening along roads and railways, and around villages. Foreign embassies and missionaries brought in eucalypts from plantings in Italy, France and elsewhere for ornamental use. Chinese living overseas and Chinese diplomatic missions were also responsible

for introducing eucalypts. A Chinese consul in Italy, Wu Zonglian, was probably responsible for some of these introductions. In 1910, he wrote 'An illustrated introduction to the *Eucalyptus*' that was probably the earliest Chinese publication describing eucalypts. He also advised the emperor that eucalypts could grow in southern China as far north as the Changjiang (Yangtze) River (Zhuang 1982, in Bai and Gan 1996).

Most seed of the early introductions was almost certainly collected from planted trees, so the original Australian sources were not recorded, and often the seeds were incorrectly named (Wang 1991). Until the late 1940s, it appears eucalypts were planted only in gardens and along roadsides (Qi 2003). In 1935, Chen Jitang, a warlord in Guangdong province, made one of the earliest significant plantings when he installed lemon-scented gum (*Corymbia citriodora*) along a highway in Hepu County, Guangxi (Gu 1990). In 1946, this species was introduced from Hong Kong, and a large number of trees were planted as ornamentals in the county town and along roadsides in Lingshan County, Guangxi. In Yunnan, similar roadside and garden plantings were occurring with *E. globulus* until the end of the 1950s (Wang et al. 1989; Qi 2003). In Sichuan, species such as *E. camaldulensis*, *E. globulus* and *E. robusta* were introduced from natural stands in Australia and plantations in Algeria, India and South Africa, and had been included in plantings since 1910 (Li and Hu 2003). How *E. exserta* was introduced into China is not known, but it was being used in plantings (known as 'four-side' plantings) along roads, waterways etc. in Guangdong province in the 1940s (Qi Suxiong, formerly Director of Leizhou Forestry Bureau, pers. comm. 2006).

Eucalypt planting during the pre-reform period 1950–1978

It was not until after Mao Zedong came to power in 1949 and founded the People's Republic of China that planting eucalypts on a large scale for wood products was advocated. After the Ministry of Forestry was established, a policy directive was promulgated by the State Council that promoted setting up organisations to undertake a range of forestry activities including afforestation of hills and wastelands. The new government urged 'the masses' to 'make the countryside green.'

Although some eucalypt plantations were established in the period 1950–1978, overall forest production stagnated, and many areas of natural forest were converted to croplands. There is no doubt that most planting through the 1950s was to establish protection forests rather than forests for wood production. Most of these mass-forestation activities did not include post-planting tending and resulted in vast areas of poorly stocked plantations.

Soon after 1949, China began to receive help and guidance from Russian experts. The Russians recommended planting several eucalypt species in southern China to produce railway sleepers, fencing and firewood (Zacharin 1978). They also brought with them the ideas of the Russian horticulturist and plant breeder, I.V. Michurin. These had considerable influence on foresters in China. In 1954, for example, Li Lai-Yung at the Fujian Agricultural College reported the successful growth of several eucalypt species in Guangdong and Fujian and recommended extensive planting of eucalypts in south-eastern China using the techniques of Michurin (Li 1954). The use of ‘cluster planting’ and close spacing in new plantations accorded

with Michurin’s thinking, but Michurin’s ideas on genetics had little influence on forest tree improvement which, in the 1950s, was not a prominent feature of Chinese research (Richardson 1966).

In 1957, the former Chairman of the People’s Congress, Zhu De, at a national meeting on water and soil conservation, advocated extensive planting of eucalypts in southern China (Qi 2003). Chinese authorities made a decision in 1958 to concentrate most of their production forestry in areas south of the Changjiang (Yangtze) River (Richardson 1966). This favoured eucalypt planting, as it is the area where frosts are less severe.

Large-scale eucalypt plantation programs were initiated in the 1950s, using species already available in China at that time. Widespread failures were common, on account of both inappropriate species–site matching (resulting in severe frost damage in cooler regions) and the lack of site amelioration work and plantation maintenance. Growth rates were poor during the 1950s, averaging less than 7.5 m³/ha/year (Wu et al. 1994a; Liu et al. 1996).

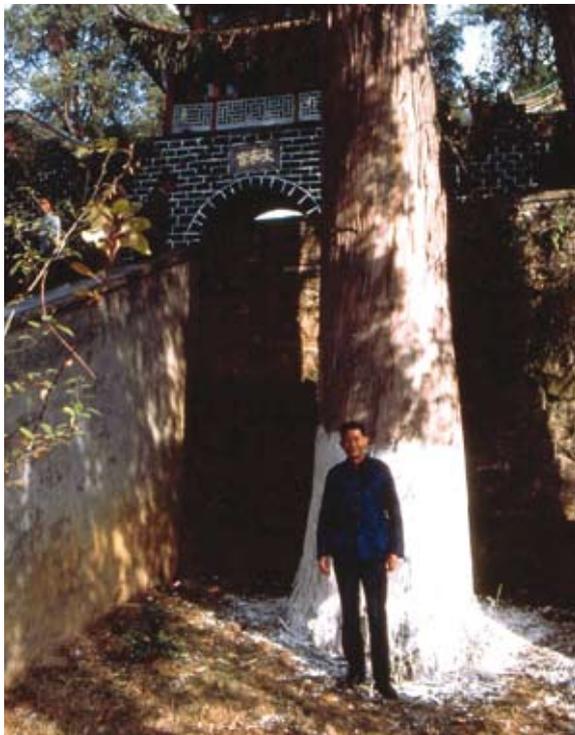


Figure 1. (a) *Eucalyptus globulus* in the grounds of the Golden Temple, Kunming, Yunnan [J. Turnbull]; (b) *E. exserta* planted an estimated 100 years ago near a village close to Zhuhai, Guangdong [Wang Huoran]

The harvesting of eucalypt leaves for their essential oils preceded the planting of the species for wood. The major compound in the essential oil extracted from *E. globulus* and *E. exserta* is 1,8 cineole, which can be used in medicines. The oil of lemon-scented gum, *C. citriodora*, is rich in citronellal, which is used in perfumery products. Rural communities were using these species to produce essential oils in the 1950s. They were grown around villages, in small woodlots or in agroforestry systems intercropped with vegetables (Richardson 1966). Initially, the oil was for local use but, in 1953, a eucalypt-oil industry developed in Guangdong province and this became a source of cash income in rural areas of southern China, especially in Guangdong, Guangxi and Yunnan. Large commercial eucalypt oil operations started on Leizhou Peninsula in the 1960s, taking advantage of the extensive eucalypt plantations. The oils produced were for local use and export and, from this small beginning, China was to become the world's largest producer and exporter of eucalypt oils (Wang and Wang 1991; Chen 2002a).

The greatest successes with eucalypt plantations were in Guangdong and Guangxi provinces. Leizhou Forestry Bureau, established in 1954 in Zhanjiang, Guangdong, was responsible for planting and extension of eucalypts on a large scale on Leizhou Peninsula. It had a research unit and, after 30 years, it had established, on four forest farms, 41,000 ha of plantations, of which 85% were eucalypts. Leizhou Forestry Bureau's first eucalypts were planted on Yuexi Forest Farm in 1954, using seeds collected from trees in 'four side' plantings. A book by Qi Suxiong, summarising experience with the young eucalypt plantations on Leizhou Peninsula, was published at the end of the 1950s (Qi 2003). The eucalypts most commonly planted in production forest on Leizhou Peninsula were *E. exserta* on the infertile sites and *C. citriodora* on the slightly more favourable sites. These two species were favoured probably because they would tolerate the infertile soils available for planting and because their narrow leaves produced an open crown that was less easily damaged by typhoons. After 15 years, the mean annual increment of *E. exserta* was 4–5 m³/ha/year and of *C. citriodora* 8 m³/ha/year (Qi Suxiong, Director of Leizhou Forestry Bureau, pers. comm. 1980). In the 1950s, establishment of protection forests of *Eucalyptus* spp., *Acacia confusa* and *Casuarina equisetifolia* was common on Leizhou Peninsula to mitigate the effects of typhoons on other crops, and to stabilise coastal sands.

Russian influence on eucalypt planting terminated abruptly in 1960 and the Chinese policy of 'self-reliance' became firmly established. This policy had implications for the productivity of eucalypt plantations as, for a long period, they were all established from unimproved local seed sources. In Guangxi, a second eucalypt forest farm, Guinan Forest Farm, was established in 1963 (Chen 2002a) to manage eucalypt plantations comprised mainly of *C. citriodora*. Dongmen Forest Farm was established in 1965 and planting began in 1966. *Eucalyptus exserta* and *C. citriodora* were planted initially. The mean annual increment of these plantations was 2.5–8.5 m³/ha/year (Wei 1996). During this period, more than 10 forest farms were set up to manage eucalypts in Guangxi region (Bai and Gan 1996). In Yunnan, large-scale planting of *E. globulus* started in the 1960s (Wang et al. 1989).

To meet demand for railway sleepers, a large number of eucalypt plantations were established along railway tracks by the Department of Railways in the 1960s in southern, south-eastern and south-central China (Qi 2003). Eucalypts were also commonly planted along roadsides by those responsible for building and maintaining roads. These plantations were generally closely planted and unthinned (Kemp 1980; Turnbull 1981).

The area of eucalypt plantations increased during the 1960s and early 1970s, and improved land races and cultural techniques were used. By 1970, there were 40,000 ha of eucalypt plantations in southern China (Bai and Gan 1996). The main species planted during that period were *E. camaldulensis*, *C. citriodora*, *E. exserta*, *E. globulus*, *E. maidenii*, *E. robusta*, and *E. tereticornis*. During the 1970s, eucalypts were used for construction timber, mining timbers, railway sleepers, pilings, poles, tool handles, fuelwood, essential oils and to support honey production (Qi 1979; Yang 2003). It was claimed that about 200 species, varieties and hybrids of *Eucalyptus* had been introduced and were growing in China in the late 1970s (Leizhou Forestry Bureau 1978), but Wang and Brooker (1991) located only 102 species in field surveys and herbarium examinations. Unfortunately, as Bevege and Curtin (1983) found at Dongmen State Forest Farm, for those species tested for plantations, 'records are scarce, identifications suspect and provenances unknown.'

The Cultural Revolution (1966–1976) seriously disrupted the scientific research in forestry that had started in the 1950s. During the revolutionary period, China was frequently in chaos, research institutes were dissolved, and researchers were dispersed to do manual work as part of the re-education of intellectuals (FAO 1982). A consequence of this disruption was that Chinese foresters were unable to take advantage of the seeds of many eucalypt species that became available at the time, and little progress could be made on species and provenance testing.

In 1963, the Forest Research Institute² in Canberra, Australia, began to collect seed of many provenances of several important eucalypts from natural forests in Australia and adjacent islands and distribute it to forest research organisations throughout the world for tree improvement research (Turnbull et al. 1980). On 25 October 1971, the General Assembly of the United Nations recognised the People's Republic of China as the sole legitimate government of China and, to mark this, FAO arranged for the Forest Research Institute to send a small selection of seeds of eucalypt species to China. The seed consignment included *E. urophylla* and tropical provenances of *E. camaldulensis* and *E. tereticornis* that had not previously been introduced into China. Some of this seed reached the Leizhou Forestry Bureau and was planted as a species trial in 1974 (Figure 2). Between 1975 and 1980, there were a number of ad hoc introductions of eucalypt species to China by visiting individuals and delegations, but the fate of most of these is not recorded (Turnbull 1981).

Small-scale, rudimentary tree-improvement programs with eucalypts started in southern China in the 1970s, with limited species–provenance testing and progeny testing (Chen 2002a). The emphasis in eucalypt breeding was to improve stem straightness and growth rate through hybridisation and selection. Stabilisation of a selected natural hybrid, with *E. exserta* as one parent, known as *E. 'leizhou No. 1'* or *E. 'leilin No. 1'*, was the main aim of tree improvement on the Leizhou Peninsula. At least initially, *E. 'leizhou No. 1'* was not recognised as a hybrid but simply as a variant of *E. exserta* (Leizhou Forestry Bureau 1977). This hybrid was used extensively on Leizhou Peninsula and Hainan Island, where many eucalypt plantations were being

established (Qi 1990). The mean annual increment of eucalypt plantations in 1980 was reported as 6–10 m³/ha/year, but many plantations may have been less productive (Turnbull 1981). There was great potential to increase productivity significantly through the use of better-adapted genetic material and implementation of improved fertilising technologies and modern silvicultural techniques (Carter et al. 1981b).

Books by Professor Kuan-Zhao Hou of the South China Botanical Institute, Chinese Academy of Sciences ('Eucalypts grown in China') and Qi Suxiong ('Eucalypt cultivation') were published in the 1950s but, with the expansion of eucalypt plantations in the 1970s, there was a need for more up-to-date information to be distributed and exchanged. In 1972, the National Eucalypt Science and Technology group was formed and a specialised journal 'Eucalypt Science and Technology' published (Qi 2003). Qi Suxiong also published a book, 'Eucalypt cultivation and planting' (in Chinese), but Chinese foresters still had very limited access to information on eucalypt plantation practice outside



Figure 2. Eucalypt species trial planted 1974 at Leizhou Forestry Bureau, Guangdong [J. Turnbull]

2 The Forest Research Institute became the CSIRO Division of Forestry in 1975.

their country. This was partially remedied in 1979, when FAO published a Chinese translation of 'Eucalypts for planting', a classic book describing the cultivation and utilisation of eucalypts around the world (FAO 1979).

Eucalypt planting during the post-reform period 1978–1990

Eucalypt planting moved into a transition phase after implementation of the 1978 policy decisions on reform and opening to the outside world. This started with Chinese foresters having greater access to information on eucalypt plantation practices outside their country. For example, in October 1978, when Chinese foresters attended the 8th World Forestry Congress in Jakarta, Indonesia, Dr Pan Zhigang of the Chinese Academy of Forestry in Beijing used this opportunity to make contact with Australian forest researchers and begin the exchange of tree seeds, especially eucalypts, with CSIRO's Australian Tree Seed Centre.

Recommendations by visiting technical missions (e.g. Carter et al. 1981b), and overseas study tours by Chinese officials, helped raise awareness of the progress that had been made elsewhere on species and provenance selection and development of management practices. Forestry personnel from Guangxi benefited from a study tour to Brazil organised by the Dongmen project. Staff of the Australian National University's Department of Forestry visited the South Central Forestry University in Hunan and Nanjing Forestry University in 1985, and a reciprocal visit was made to Australia to inspect eucalypt forests and discuss educational opportunities. Other Chinese foresters made study tours, or had training in eucalypt silviculture, in France and South Africa. Within China, information sharing occurred through the Southern Eucalypt Research Association, which was established to stimulate eucalypt plantation development (Qi 2003). It had representatives from 12 southern provinces.

In the period up to 1985, the quality of planting and subsequent plantation maintenance received relatively little attention, so the productivity of most eucalypt plantations was low. The range of species being used was limited to *E. botryoides*, *E. camaldulensis*, *E. exserta*, *E. 'leizhou No. 1'*, *E. globulus*, *E. maidenii*, *E. robusta*,

E. tereticornis, *E. '12 ABL'* and *C. citriodora* (FAO 1982). *Eucalyptus '12 ABL'* is a land race of *E. tereticornis* originating from a single tree in Madagascar that was introduced into China about 1979 and widely planted in tropical areas. Cooperative projects with Australian agencies demonstrated the potential to increase productivity of plantations by using selected species, modern nursery techniques and efficient plantation-management practices. When the Ministry of Forestry introduced a new policy promoting 'fast-growing, high-yielding' plantations for timber production in 1985, the outdated and inefficient practices in use at that time in eucalypt plantations began to be replaced by more modern technologies (Table 5). Changes to previous routine practices were evident in some plantations of eucalypts by the late 1980s.

Eucalypt plantation practices 1978–1985

The following description relates mainly to eucalypt plantation practices in Dongmen State Forest Farm and the forest farms of Leizhou Forestry Bureau, which were probably the most technologically advanced of the state forest farms growing plantation eucalypts, and is based on information in Turnbull (1981) and Bevege and Curtin (1983). The species planted were mainly *E. exserta* and *C. citriodora* of unknown provenance, and the highly variable, hybrid land race, *E. 'leizhou No. 1'*.

Very-low-cost nursery techniques were developed locally (Figure 3). Eucalypt planting stock was raised in soil bricks rather than plastic or peat containers. The blocks were made in sunken beds where fertile loam was mixed with calcium magnesium phosphate and animal



Figure 3. Raising *Eucalyptus exserta* in the nursery at Leizhou Forestry Bureau in 1980 [J. Turnbull]

manure. Each bed was watered, levelled and the soil mix cut into blocks $8 \times 8 \times 12$ –15 cm. Seeds were either broadcast sown and the resulting seedlings pricked into the blocks, or sown directly into a small depression at the centre of each block. At Leizhou, each block contained two seedlings. The seedlings were fertilised with a urea solution and were 20–30 cm tall and ready for planting out in 60–90 days.

Existing vegetation was cleared and burned, and stumps were removed from planting sites. The sites were completely ploughed, often two or three times, with alternate harrowing (Figure 4). On sloping ground, the planting area was terraced and cultivated by hand. Fertiliser was applied either before or at the time of planting. At Dongmen, a phosphatic fertiliser of doubtful composition, and ash from burnt litter or vegetation, were placed near each tree when available. At Leizhou, animal manure or vegetable matter was applied in each planting hole. Trees were planted at very close spacing, with the stocking for *E. exserta* 3,750–4,500 trees/ha and for *C. citriodora* about 2,250 trees/ha. The trees were tended by hand or cultivated by machines between the rows once or twice a year for 3 years after planting.

Most plantations were grown on a 10–20-year rotation with two or three thinnings. Final stocking was 1,500 trees/ha for *E. exserta* and 900 trees/ha for *C. citriodora*. Much of the wood was grown with the objective of producing stems 14–16 cm diameter for use as pit props. It was also used for round construction and roofing timber and small turnery items. At Leizhou, branches



Figure 4. Intensive site cultivation in a new eucalypt plantation at Leizhou Forestry Bureau in 1980 [J. Turnbull]

were harvested and chipped for use in fibreboard manufacture. Foliage was distilled for eucalypt oil, and the stumps, when dug out, were used as fuel. After harvesting, the stumps of *E. exserta* were usually allowed to coppice for the subsequent rotation but this practice was less successful with *C. citriodora*.

In the years following the end of the Cultural Revolution, forest research slowly resumed, but progress was hindered by lack of funds, inadequate equipment and the poor training of scientists. The central government recognised the situation and started negotiating with the World Bank for funding of the Forest Development Project (1985–1990) to support afforestation on state forest farms in Heilongjiang, Sichuan and Guangdong, and to strengthen research at four provincial research institutes. A review of these institutes, three of which were in eucalypt-growing provinces (Guangdong, Guangxi and Sichuan), found serious deficiencies in training, research management skills, research methods and equipment. A particular deficiency was research into forest soils and tree nutrition, including fertiliser technology. Research was lacking into modern mensuration techniques and economic issues relating to yields of plantations in response to a range of tending, fertilising and thinning regimes (ACIAR 1986). It is clear that researchers faced many constraints, and research support for plantation forestry in southern China was consequently very weak at the time. Before 1982, the situation was exacerbated by the location of the Research Institute of Tropical Forestry³ of the Chinese Academy of Forestry, on Hainan Island, which severely restricted its research in mainland provinces. In October 1981, it moved from Hainan to Guangzhou in Guangdong province.

Eucalypt plantation practices 1985–1990

A new policy promoting ‘fast-growing, high-yielding’ plantations for timber production introduced by the Ministry of Forestry in 1985 produced a burst of eucalypt planting. An estimated 300,000 ha was planted under this program (van Bueren 2004). Apart from promoting the siting of plantations on better soils, using higher quality nursery stock, and implementing improved management techniques, the management objective changed from a regime primarily producing

3 Formerly the Tropical Forest Experiment Station located at Jianfengling, Ledong County, Hainan

mining timber to one producing woodchips for pulp and paper and other reconstituted wood products. Visiting Australian foresters (e.g. Turnbull 1981; Bevege and Curtin 1983) had earlier suggested the potential of eucalypt plantations in China to provide good quality material for paper pulp, fibreboard and particleboard.

This change of government policy affected the choice of eucalypt species for planting. Interest in planting fast-growing species with wood properties suitable for pulp increased and research focused on species such as *E. grandis* and *E. urophylla* that were being grown for pulpwood in Brazil, South Africa and other countries.

Table 5. Evolution of eucalypt plantation technology in China from 1978 to 2006

1978–1985	1985–1990	1991–2006
Planning		
Little use of cost–benefit or rate of return analysis	More economic analysis of returns from using different species and practices	Economic analysis of returns from using different species and practices commonly used
Few species available so species–site matching limited	More potentially useful species available so more options for species–site matching	The best species for particular sites and products identified
Minimal attention paid to socioeconomic and environmental impacts of plantations	Some attention paid to socioeconomic and environmental impacts of plantations	Greater attention paid to socioeconomic and environmental impacts of plantations
Low-quality research with poorly designed experiments	Improved research with better design and analysis of experiments	Better-trained scientists with continued improvement of design, analysis and reporting of experiments
Planting material		
Tree seed collected locally with minimal selection Original provenances unknown	Seed orchards planted and greater interest in superior, source-identified seeds	Superior, source-identified seeds or clones used routinely
Nursery practices outdated and seedling quality low	Improved containers and potting mixes resulting in higher quality seedlings	Modern nurseries developed producing high quality plants
Clones not used	Clones starting to be used	Selected clones of pure species and hybrids commonly planted
Silviculture		
High planting densities	Reduced planting densities	Planting densities adjusted to meet plantation objectives
Limited fertilisation mainly with organic materials	More use of inorganic fertilisers at specified rates	Inorganic fertilisers at specified, near optimal rates commonly applied Nutritional deficiencies identified and treatments specified
Intensive soil preparation and/or pit planting	Reduced site preparation	Minimum cultivation techniques increasingly used
Planting up and down slopes	Contour planting on sloping land	Contour planting on sloping land

Their selection and breeding was accompanied by research to determine optimum levels of site management, especially fertilising regimes.

In Guangxi, the Dongmen State Forest Farm Eucalypt Afforestation Project started field research on species and provenances, site preparation techniques, fertiliser regimes and volume tables in 1983. Results from this initial research started to become available from about 1985. In the years to follow, these studies were expanded and new research started on nursery techniques, clonal propagation, tree breeding and wood density. Achievements at Dongmen have been summarised by McGuire et al. (1988), Pegg (1990) and Wei (1996).

By 1986, the project had had over 600 visitors from state forest farms, research institutes and universities from several provinces. Project staff prepared 41 technical communications between 1982 and 1989. Technical exchange seminars were also organised to disseminate results, and senior officials from the Ministry of Forestry recommended Chinese foresters implement the new technologies (Cameron et al. 1988). Following a review in 1986, the project was extended to 1989. After the project terminated, many of the research activities were continued and expanded by staff of the Guangxi Forest Research Institute in Nanning. They continued to receive advice periodically from Richard Pegg and other Australian researchers formerly associated with the project.

It is difficult to estimate how much influence the Dongmen project had on eucalypt plantation forestry in southern China before 1990, but it had massive effects on eucalypt plantation forestry in China in subsequent years. Its impacts included:

- demonstrating the potential for increasing plantation productivity through species and provenance selection, cheaper site preparation methods, wider spacing and fertiliser application
- providing a model for other researchers, in that its recommendations were based on well-designed experiments amenable to statistical analysis and interpretation
- demonstrating the importance of including wood studies in a breeding program and the benefits of having a well-equipped soil and plant laboratory with trained staff

- training Chinese foresters in eucalypt ecology and silviculture.

Most of the research in the Dongmen project took place in Guangxi province. In 1984, a complementary research project supported by ACIAR was planned to test a wider range of Australian tree species and provenances in a variety of environmental conditions in other provinces. The project's objectives were to:

- determine which Australian broadleaved tree species had the potential for domestic and industrial wood production in China
- explore the ecological potential of Australian broadleaved trees for landscape restoration in China
- provide base populations from which tree breeding and advanced tree-improvement research could be developed
- improve the scientific capacity of Chinese scientists in trial design, statistical analyses, computing techniques and tree breeding.

Beginning in 1986, seeds of a wide range of eucalypt species and provenances of known origin from CSIRO's Australian Tree Seed Centre were sent to China. The new genetic resources were compared to local selections in field trials on representative sites in provinces where an expansion of eucalypt plantations was planned. Trials were established in Yunnan, Fujian, Guangdong and Hainan provinces between 1986 and 1988. Early results confirmed that some of the new introductions were outperforming the local selections, often doubling wood-volume production. Preliminary results were published in English by Chinese scientists in an ACIAR book (Boland 1989) and, following an international workshop on 'The use of Australian trees in China', held in 1988 in Guangdong, in Chinese. To assist Chinese foresters understand the taxonomic relationships of eucalypt species, one of the project leaders, Wang Huoran (Wang 1986) translated 'A classification of the eucalypts' by L.D. Pryor and L.A.S. Johnson (1971) for publication in China. The ACIAR and Dongmen projects also supported translation and publication in Chinese of another valuable textbook on eucalypts, 'Eucalypts for wood production', edited by W.E. Hillis and A.G. Brown (1978).

Following an external review by Stewart and Mannion (1988), the project was extended until 1993. Existing trials were maintained and monitored, new trials established, a breeding program for *E. globulus* was initiated based on a breeding plan (Raymond 1988) and demonstration plantations of promising species/provenances, e.g. *E. camaldulensis* and *E. urophylla*, were established to provide large quantities of semi-improved seed. In 1992, a workshop 'Australian tree species research in China' was held in Zhangzhou, Fujian, to consolidate the results of the field trials and to extend the information to a number of Chinese forestry organisations. The workshop proceedings were published by ACIAR in English (Brown 1994). A feature of this collaborative project was the high level of responsibility assumed by the Chinese forest researchers in implementing the field trials, analysing results and preparing reports for publication.

Although Australians were playing a major role in helping their Chinese collaborators develop a range of improved techniques, there were also significant inputs from other countries. Of particular importance was the transfer of technology from Brazil. In the 1980s, some Brazilian companies had intensified the management of their plantations using superior planting material in clonal plantations and applying intensive fertiliser and weeding regimes. They used vegetative propagation to clone selected genotypes, especially to take advantage of hybrids. Seeds of the hybrid *E. grandis* × *E. urophylla* produced in Brazil were sent to China in 1983 and included in field trials at Dongmen. In addition, Chinese research on vegetative propagation of eucalypts was assisted by an FAO-facilitated visit by Edgard Campinhos, a Brazilian expert (Campinhos 1987; Campinhos and Ikemori 1988).

The area of eucalypt plantations had reached over 500,000 ha by the beginning of 1990, with the main plantations in tropical and subtropical Guangdong (175,000 ha), Hainan (175,000 ha), Guangxi (100,000 ha) and Yunnan (75,000 ha). Lack of suitable cold-tolerant species inhibited the planting of eucalypts in areas where frosts were severe. Mean annual growth rates of the plantations were low, estimated at 4–7 m³/ha, and few received adequate fertilisation despite research showing the benefits of this practice on the nutrient-deficient soils of southern China. Nevertheless, the plantations were beginning to make a significant contribution to domestic wood production,

and some woodchips were exported. In 1990, over 200,000 tonnes of eucalypt woodchips were produced in Hainan, Guangdong and Guangxi, most of them exported to Japan (Wang and Zhou 1996).

To mark the centenary of eucalypt growing in China, an international eucalypt symposium was held in Zhanjiang, Guangdong in 1990, and a book '*Eucalyptus in China*' edited by Qi Suxiong was published. A revised edition of this book appeared in 2002 (Qi 2002).

Developments in research and planting 1990–2006

By 1990, forest research had provided a suite of new technologies that made eucalypt plantations commercially attractive for investors. Significant productivity gains were made between 1990 and 2001, with the adoption of the new technologies (Table 5), and further gains followed with the release of new clones (Yang 2003). Information on the main research activities and the entities responsible for plantation development in this period is summarised below. Research achievements are described more fully in the section 'Domestication of eucalypts in Australia'.

Research

Most of the research was conducted by Chinese scientists, often collaborating to a greater or lesser extent with scientists from Australia and elsewhere, and sometimes partially funded under international or bilateral development-assistance programs. Research results were disseminated to potential users through extension-service personnel, conferences and workshops, conference proceedings, specialised training courses, technical communications and demonstration areas.

Between 1990 and 2001, NAP and FRDPP supported a research group on eucalypts that selected superior provenances of *E. urophylla* for typhoon-prone areas and *E. tereticornis* for western Guangdong province, made interspecific hybrids, and assessed variation in wood properties in provenance trials of *E. tereticornis* and *E. camaldulensis*. Other research investigated spacing of trees in plantations, site preparation, mycorrhizas, and selection for resistance to bacterial wilt disease. The research activities of this group were

also supported by FRDPP. Both projects stimulated new institutional linkages between forest researchers, extension personnel and plantation growers to encourage the implementation, in general plantation practice, of new improved technologies derived from research (Table 5).

Eucalypt plantation development in Hainan was assisted by a 1993–98 project, ‘Demonstration of classified management and sustainable utilisation of tropical forests in Hainan Island’, supported by the International Tropical Timber Organization (ITTO) (Bai and Gan 1996). The project was implemented jointly by the Chinese Academy of Forestry and Hainan Provincial Forestry Bureau. Part of the project researched vegetative propagation of *E. urophylla*, *E. tereticornis* and *E. 12 ABL* by cuttings, and established a nursery and about 1,000 ha of demonstration clonal plantations at Danzhou Forest Farm. Technical training in tree-breeding techniques was also provided.

The International Foundation for Science (IFS) has supported the research of individual Chinese scientists working on eucalypts. From 1988 to 1995, IFS funded provenance research on *E. tereticornis* and species selection for eucalypt oils by the CAF Research Institute of Forestry. The IFS, together with the National Natural Science Fund, also supported a RITF project, ‘Construction of genetic linkage maps of *E. urophylla* and *E. tereticornis*’, over the period 1997–2000 (Bai et al. 2003).

The China Eucalypt Research Centre (CERC) was established in 1992 as an institution under the Chinese Academy of Forestry. Its main role is to undertake key national eucalypt research projects and collaborate with other research groups, such as RITF and provincial forest research institutes. CERC’s research includes investigations into genetic engineering, producing high-value, large-diameter logs, and sawing technologies. It facilitates the application of research findings, provides technical assistance in tree breeding and propagation, and delivers technical services and training to the national network of eucalypt extension stations (Yang 2003; CAF 2006). CERC was conceived as a joint China–Australia initiative supported by the Australian Agency for International Development (AusAID) (Griffin et al. 1988; Midgley and Yang 1992), and, although this did not eventuate, arrangements were made for three of CERC’s staff to receive postgraduate

training at Australian universities and for others to receive specialised short-term training in Australia. In addition, substantial quantities of eucalypt seeds to provide base populations for tree improvement were given to CERC through CSIRO’s Australian Tree Seed Centre. These populations are the basis of many current tree breeding activities (S.J. Midgley, Salwood Asia Pacific, pers. comm. 2006).

A cooperative eucalypt research group, started in 1972 and coordinated by Qi Suxiong, was made up of representatives of five southern provinces. The group was renamed the ‘Eucalyptus Research Association of Southern China’ in the early 1980s. In 1990, it became the ‘Division of Eucalyptus’ in the Chinese Society of Forestry. This group has 500 members in 18 provinces, and initiates much of the new research into eucalypt plantations (Yang 2003).

Key national research initiatives on eucalypts were included in the Eighth (1991–1995) and Ninth (1996–2000) National Five-year Plans, e.g. ‘Improved variety selection and cultivation technology on *Eucalyptus* species for pulpwood’ in 1996–2000. The Science and Technology Department of the State Forestry Administration has, since 1996, enabled the Sino-Forest Corporation (Canada) to invest 3% of its annual budget for plantation management in collaborative research projects on eucalypt breeding and cultivation with Nanjing Forestry University, RITF, and Guangdong, Guangxi and Jiangxi provincial research institutes (Qi 2003). Other commercial eucalypt growers, such as Stora Enso, APP and RGM/APRIL, also support research and development (R&D) activities.

ACIAR continued to fund cooperative research on eucalypt growing and wood processing. Between 1991 and 2006 four major research projects were supported.

- Increasing productivity of eucalypt plantations in China by inoculation with ectomycorrhizas and nutrient application (1991–1998)

Research partners: *Australia*—CSIRO Forestry and Forest Products, Murdoch University; *China*—CAF Research Institute of Tropical Forestry, Chuxiong Forest Research Institute, Gaoyao Forest Bureau, Kunming Institute of Botany, Xinhui Forest Bureau.

- Development of germplasm and production systems for cold-tolerant eucalypts for use in cool regions of southern China and Australia (1999–2004)

Research partners: *Australia*—CSIRO Forestry and Forest Products, Centre for Forest Tree Technology of the Department of Natural Resources and Environment (Victoria), Forestry Tasmania; *China*—China Eucalypt Research Centre, Fujian Forestry Department, Guangxi Forest Research Institute, Hunan Forestry Department, Yunnan Academy of Forestry.

- Eucalypts for water: managing forest plantations in China and Australia for sustained productivity and environmental benefits (1999–2003).

Research partners: *Australia*—Department of Natural Resources and Environment (Victoria), CSIRO Land and Water, University of Melbourne; *China*—CAF Research Institute of Tropical Forestry, South China Institute of Botany, China Eucalypt Research Centre.

- Improving the value chain for plantation-grown eucalypt sawn wood in China, Vietnam and Australia: sawing and drying (2005–2009)

Research partners: *Australia*—CSIRO Forestry and Forest Products; *China*—China Eucalypt Research Centre; *Vietnam*—Forest Science Institute of Vietnam.

Planting

Eucalypts played an increasingly important role in plantation forestry in southern China after 1990. Government policies in the early 1990s encouraged provinces, prefectures and counties to facilitate development of eucalypt plantations, chipping factories and pulp mills to stimulate export trade. Strategies were developed to expand eucalypt plantations in each province. In Guangdong, for example, the aim was to establish 400,000 ha of intensively managed eucalypt plantations with an annual yield of 12–15 m³/ha (Bai and Gan 1996). By 1996, loans from the NAP enabled about 60,000 ha of eucalypts to be planted. Another 37,000 ha were subsequently planted with loans from the FRDPP. The private sector, mainly non-state commercial forestry enterprises (including new shareholding entities) and farmers established most of the eucalypt plantations after the 1990s (Qi 2003).

Since 1995, the provinces of Guangdong, Guangxi and Hainan have become the focus of eucalypt plantation development for the pulp and paper industry. Fujian is also expected to have substantial areas of eucalypt plantations in the future. These provinces have attracted some of the world's largest pulp and paper companies, which are actively developing their resource base and planning wood-based pulp mills. They include Indonesia-based Asia Pulp and Paper (APP), Singapore-based RGM International (APRIL), Finland-based Stora Enso and UPM-Kymmene, and Japan's Oji Pulp and Paper. The main species being planted are *E. urophylla*, *E. tereticornis*, *E. '12 ABL'* and several hybrids including *E. grandis* × *E. urophylla*, *E. urophylla* × *E. grandis* and *E. urophylla* × *E. tereticornis* (Barr and Cossalter 2004). Many of the *E. '12 ABL'* clones and seedlings now being deployed may be hybrid combinations involving *E. grandis* and other eucalypt taxa (Arnold 2005).

It was estimated in 2002 that the largest areas of eucalypt plantations were in Guangdong (570,000 ha), Hainan (350,000 ha), Guangxi (340,000 ha) and Yunnan (150,000 ha) (Qi 2002). Since then, several initiatives have established an estimated additional 150,000 ha of these plantations, which are now thought to total about 1.5 million ha (UNDP 2006). The annual planting rate is about 90,000 ha (Arnold 2005). There are also over 1.8 billion trees in 'four-side' plantings (equivalent to an additional 350,000 ha), more than half of which are in Yunnan and Sichuan (Chen 2002a). Seed orchards now produce improved, high-quality seed, associated with which has been the application of vegetative propagation techniques (a combination of tissue culture and mini-cuttings) to produce clones. Most plantations in warmer coastal regions are now based upon clones selected for superior performance under southern Chinese conditions. Elsewhere, seedlings are used, because the species planted are difficult to propagate as rooted cuttings (e.g. *E. globulus*, *E. maidenii*, *E. smithii* and *E. dunnii*), or improved clones have not been adequately developed.

Until 2004, the focus of eucalypt plantations was on fibre production for export woodchips, MDF and particleboard (Figures 5 and 6). More than 20 MDF and particleboard factories in southern China were using about 3 million m³ of eucalypt wood and, as large-scale pulp mills were not yet operating, most of the available eucalypt woodchips were exported to Japan, South Korea and Taiwan (Yang 2003; Barr and Cossalter 2004).

The MDF and particleboard industries are still operating and will compete with future pulp mills in China for eucalypt wood fibre.

The Hainan Jinhai Pulp and Paper Co., a joint venture between APP and Hainan Forestry General Corporation, has operated a mill in Hainan producing bleached hardwood kraft pulp (Figure 7 and 8) since 2004. The installed annual capacity is 1.1 million air-dried tonnes, requiring 4.6 million m³ of debarked wood each year.

Asia Pulp and Paper has invested in pulpwood plantations in Guangdong, Guangxi and Hainan provinces since 1995 and, at the end of 2003, had 63,500 ha in Hainan, 30,000 ha in coastal Guangxi and 26,900 ha at two sites in the north and north-east of Guangzhou.

The company's plantation program has been mainly on land collectively owned by townships and villages, and on small individual farms. If, within the next 6 years, APP is able to double the area of its current plantations to 240,000 ha and manage them sustainably, they will produce about 75% of the fibre needs of the Hainan pulp mill. This is based on the assumption that, each year between 2004 and 2009, APP will be able to plant and replant a total of 40,000 ha, an area it has so far not been able to achieve (Cossalter 2004). The company has plans to develop 150,000 ha of eucalypt plantations in Yunnan, but it appears that, even with the most optimistic planting scenario, it will have to secure fibre from other sources and/or import significant quantities of woodchips.

Table 6. Main eucalypt species planted in China in 1992 and 2004

Species	Year introduced	1992	2004	Main uses	Planting areas
<i>Eucalyptus camaldulensis</i>	1910	x	x	Pulp & paper, firewood	Guangdong, Hunan, Sichuan
<i>E. dunnii</i>	1985		x	Pulp & paper, MDF ^a , veneer	northern Guangxi, Hunan, Fujian
<i>E. exserta</i> and <i>E. 'leizhou No. 1'</i>	1940s	x		Pulp & paper, mine timber, oil	Guangdong, Guangxi, Hainan,
<i>E. globulus</i>	1896	x	x	Pulp & paper, MDF, mine timber, oil, firewood	Guizhou, Sichuan, Yunnan
<i>E. grandis</i>	1982	x	x	Pulp & paper, MDF, mine timber	Sichuan, Yunnan
<i>E. maidenii</i>	1964	x	x	Pulp & paper, MDF, mine timber, firewood	Guizhou, Sichuan, Yunnan,
<i>E. saligna</i>	1982		x	Pulp & paper, MDF, veneer	northern Guangxi, Hunan, Fujian
<i>E. smithii</i>	1988		x	Pulp & paper, MDF, mine timber, oil	Yunnan, Sichuan
<i>E. tereticornis</i>	1890	x	x	Pulp & paper	Hainan
<i>E. '12 ABL'</i>	1979	x	x	Pulp & paper	Guangdong, Hainan
<i>E. urophylla</i>	1974	x	x	Pulp & paper, MDF, veneer	Fujian, Guangdong, Hainan Guangxi
<i>E. urophylla</i> × <i>E. grandis</i> and other hybrids	1983		x	Pulp & paper, MDF	Guangdong, Guangxi, Yunnan
<i>Corymbia citriodora</i>	1930s	x		Mine timber, oil	Guangxi, Guangdong

^a MDF = medium-density fibreboard.

Source: based on Wang et al. (1994a), Chen (2002a), Li and Hu (2003), van Bueren (2004) and R. Arnold (pers. comm. 2006).

The Finnish–Swedish company Stora Enso established Guangxi Stora Enso Forestry Co. Ltd in 2002 and began planting eucalypts near the coast in south-western Guangxi to provide raw materials for a proposed integrated forest–pulp–paper industry in southern Guangxi supporting a 600,000 air-dried tonnes/year chemical pulp mill. By 2005, Stora Enso was managing 20,000 ha of plantations, mainly eucalypts, and aims to manage 120,000 ha by 2010 (UNDP 2006). There are complex land-tenure issues in Guangxi, as in other parts of southern China, so it is unlikely that the company will be able to control the large resource base needed for its pulp mill. Hence, a variety of contractual arrangements will need to be made with collectives and private growers. The Guangxi Department of Forestry recently decided to turn over large areas of forest farms to Stora Enso and APP because of their difficulties in leasing land. In September 2006, Beihai City government signed an agreement with Stora Enso to transfer control of 30,813 ha of land or plantations in the period 2006–2008. This will bring land under the control of Stora Enso to nearly 100,000 ha (D.G. Nikles, Department of Primary Industries and Fisheries, Queensland, pers. comm. 2006).

In western Guangdong, there are large eucalypt plantations on Leizhou Peninsula and adjacent areas in Zhanjiang and Maoming prefectures. It was in this area that the joint venture company Fuxing–UPM Kymmene began, in 2003, to investigate and prepare for wood supplies for a future bleached hardwood kraft pulp mill of 700,000 air-dried tonnes/year capacity (Cossalter 2004). From 2003 to 2007, it planned an overall program of 200,000 ha, of which 45% would be on land with collective and individual user rights, 25% on leased land and 30% under wood supply contracts. Although this region has almost sufficient wood resources to supply a mill of this size, a large part of the resource is committed to other users and much of the mill's wood needs will have to come from new plantations. Land availability is then a problem, as there is competition from several agricultural crops. In November 2004, after studies of local conditions and the availability and cost of wood for a modern large-scale pulp mill were concluded, UPM withdrew from the joint-venture company and the future of a pulp mill in the region is uncertain. In southern China, market prices for delivered pulpwood are well above



Figure 5. Eucalypt wood chips being exported from Zhanjiang, Guangdong [C. Cossalter]

the mean cost in the rest of the world, and this raises questions about the economic competitiveness of wood-based pulp production in this region (Cossalter 2005).



Figure 6. Medium density fibreboard produced from eucalypts at a factory in Zhanjiang, Guangdong [C. Cossalter]

Sino-Forest Corporation is the largest foreign-owned forestry plantation company in China in terms of the area of plantation under management. This Canadian corporation grows and harvests trees for use in China's pulp and paper, furniture, construction and interior decoration industries. It owns and manages plantations in Guangdong, Guangxi, Jiangxi and Fujian in southern China. Most of its plantations are of *Pinus* species but it currently has 38,000 ha of eucalypts, mainly *E. grandis* × *E. urophylla* (Sino-Forest 2006).

In Guangxi, Japanese companies Oji Paper Co. Ltd and Marubeni Corporation have a joint tree-planting project and have established a 100% foreign-owned joint-venture company, Guangxi Oji Plantation Forest Co. Ltd. Marubeni is supporting Oji Paper in the current project based on experience gained in developing and importing eucalypt chips from China since 1987. Eucalypt planting started in 2002 with a target area of 6,000 ha (JOPP 2005) and harvesting will commence in 2008. Oji Paper and Marubeni have a second joint venture with the Chinese company Guangdong Petro-Trade Development to set up eucalypt plantations. This



Figure 7. Asia Pulp and Paper pulp mill on Hainan Island [C. Cossalter]

joint venture company, Huizhou Nanyou Forest Development, aims to plant 33,000 ha of eucalypts in the Huizhou area, Guangdong, by 2008, to provide 200,000 bone-dry tonnes/year of woodchips. The area will be extended to 60,000 ha in a second phase. The woodchips will go to the group's planned pulp and paper mill at Nantong, Jiangsu province (Oji Paper 2005).

In Fujian and north-eastern Guangdong, APRIL, a company within RGM International based in Singapore, has a total plantation target of at least 150,000 ha to provide a wood resource for a proposed pulp mill in coastal Fujian (R. Arnold, RGM/APRIL, pers. comm. 2006).

Eucalypt planting in south-central China has been mainly on a small scale to provide fuelwood and round timbers for local use, and essential oil. Most of Yunnan's plantations are of *E. globulus*, with small areas of *E. maidenii*, *E. smithii*, *E. grandis* and *E. urophylla* × *E. grandis*, determined by local climatic conditions.

Apart from in Yunnan, *E. maidenii* is grown in Sichuan and Guizhou, and the total area is about 10,000 ha (Li et al. 2003c). *Eucalyptus saligna* and *E. dunnii* have been planted since 1998 in cooler parts of Fujian and Hunan. There are now about 42,000 ha of eucalypt plantations in Hunan, 85% of this area being of *E. dunnii*, and in northern Guangxi and Fujian there are about 21,000 ha of *E. dunnii* planted (R. Arnold, RGM/APRIL, pers. comm. 2006).

Although there has been active development of eucalypt plantations in southern China by companies planning integrated forest–pulp–paper industries, they face obstacles in their efforts to secure an adequate plantation land base and it is likely that they will remain largely reliant on imported wood chips beyond 2009 (Cossalter 2004). More extensive planting of cold-tolerant eucalypts in provinces such as Fujian, Hunan, northern Guangxi and, possibly, Jiangxi are likely to boost local supplies of wood fibre.



Figure 8. Paper factory in Guangzhou, Guangdong [C. Cossalter]

Economics of plantations

Domestication of eucalypts in China has progressively resulted in higher wood yields and shorter rotation lengths. In general terms, yields have doubled and the rotation length has shortened from 10 years to 4–7 years (Table 7).

Xu (2003) developed scenarios and made economic analyses of different plantation establishment and management regimes. He concluded that site selection, fertilisation, and weed control are key factors affecting the economics of eucalypt plantations in southern China and predicted that future gains in productivity will come from tree breeding (30%) and improved plantation establishment and management (70%). The economic impact of research to improve the productivity of plantations in China has been substantial, with an internal rate of return on investment (IRR) of about 37% for the period 1985–2004.

In a study of the profitability and competitiveness of seven eucalypt plantations in Guangxi it was estimated that the IRR varied from 3% to 14% on hilly sites and was 18% on a flat site (Cossalter and Barr 2005). The plantation areas were in the range 75–645 ha and the investors included a private individual, a village committee, a county forest bureau and a pulp company.

The study concluded that low-to-reasonable returns on investment can be expected where uncertainty and high costs of harvesting and extraction can be avoided, and providing investments are made in appropriate silviculture for the specific site conditions. Easy access to the plantation site was of particular importance. On-site production costs on hilly sites are mainly labour (approximately 50%), fertilisers, planting stock, and supervision and transport costs. Although flat sites are less common, plantation operations on them can be partially mechanised, and productivity is higher because the costs of fertiliser application, post-planting tending operations, and harvesting and extraction are lower. Even the high-cost plantations maintained a modest delivered-wood cost advantage over foreign suppliers. However, any increases in labour costs would offset the current cost advantage that Guangxi's producers have over imported woodchips.

Although the cost of producing eucalypt wood depends on a number of factors in China, it is about twice the cost for eucalypt wood in Brazil or *Acacia mangium* wood in Indonesia (Xu 2003). High costs of delivered wood are a critical factor that may limit the competitiveness of Chinese wood growers, who ultimately must be cost-competitive with pulp imports from more efficient producer countries (Cossalter and Barr 2005).

Table 7. Average yield gains in Chinese commercial eucalypt plantations

	Pre 1991	1991–2001	Post 2001
Main species	<i>Eucalyptus exserta</i> , <i>C. citriodora</i>	<i>E. urophylla</i> , <i>E. grandis</i> , <i>E. tereticornis</i> .	<i>E. urophylla</i> , <i>E. urophylla</i> × <i>E. grandis</i> and other hybrids
Mean annual increment (m ³ /ha/year)	7	11	20
Rotation length (years)	10	7	7
Yield at harvest (m ³ /ha)	70	77	140

Source: based on Research Institute of Tropical Forestry workshop 23–25 May 2004 (van Bueren 2004)

Domestication of eucalypts in China

Tree domestication is the process of exploration and manipulation of the wild genetic resource of a tree species to derive uses and products for maximum social benefit. It usually starts with seed collected from natural stands, and benefits are derived through propagation, selection and breeding in the form of highly productive plantations. Full domestication of a tree species includes: identification and characterisation of its germplasm resources; the capture, selection, management and conservation of genetic resources; and the regeneration and sustainable cultivation of the species in managed ecosystems (Libby 1973; Leakey and Newton 1994). In widely planted and economically important timber trees, such as *Eucalyptus* species, domestication has involved systematic sampling and characterisation of genetic variation, development of optimal propagation and silvicultural techniques, and intensive breeding, including the use of molecular genetics technologies.

Intensive domestication programs have been carried out on eucalypts and pines, and the most dramatic results have been achieved with tropical eucalypts. In the Congo, more than 60 eucalypt species were originally tested, progeny trials followed and, in 1974, vegetative propagation techniques using coppice of mature trees were developed, which allowed the establishment of clonal plantations using hybrid combinations (Martin 2003). These highly productive, state-owned plantations, now yield a mean annual increment of 30 m³/ha on a 7-year rotation for pulpwood. A parallel development by a private company, Aracruz Florestal, took place in Brazil (Campinhos and Ikemori 1988). Hybrids were developed after intensive provenance trials, individual tree selection, progeny testing and development of a vegetative propagation technology using cuttings. Superior clones of *Eucalyptus grandis* and hybrids of *E. grandis* × *E. urophylla* were selected for growth

rate, stem straightness, disease resistance, and wood properties. The best clones produced 60 m³/ha/year of high-quality wood for paper production. The operations in the Congo and Brazil employed appropriate site-management techniques, such as intensive site preparation, weed control and fertilisation, to minimise constraints to tree growth.

Species used in China's plantation program before 1978 were of unknown genetic origin and history. They had not been subjected to formal selection and breeding, and may have embodied substantial inbreeding. There was a small tree-improvement program for *E. exserta* and some species trials by the Leizhou Forestry Bureau in the 1970s, but progress was severely constrained by the small base populations available in China and the lack of contact with researchers in other countries. At that time, nursery techniques were basic and fertilisers rarely used to boost growth, so it is not surprising that growth rates were usually in the range 2–8 m³/ha/year (Wei 1996). From this low base, there was great potential to improve the productivity of eucalypt plantations in China, as had been done in other countries.

International cooperation and the initiation of research projects in cooperation with Australian scientists in the 1980s greatly assisted the domestication of eucalypts in China (Chen 2002a). The research included species and provenance selection, tree breeding (population improvement), nursery practices, silvicultural practices (e.g. site preparation and planting, fertilisers, mycorrhizas) and wood quality. This section reviews the main achievements in domesticating eucalypts in China.

Selection of species and provenances

Large-scale eucalypt planting in the 1950s and 1960s used species available in China at the time. Widespread failures were common, in part due to inappropriate species–site matching, which resulted in severe frost damage in cooler regions. *Eucalyptus globulus* was the most successful species in drier, cooler areas where frosts were not severe, such as the Yunnan plateau. The eucalypts most commonly planted in production forests in the more tropical areas were *E. exserta* on soils of low nutrient status, and *C. citriodora* on slightly more favourable sites. In the 1970s, the natural hybrid, *E.* ‘leizhou No. 1’, was used extensively on Leizhou Peninsula and Hainan Island. These two species and the hybrid land race were probably favoured because they would tolerate the poor soils available for planting, and because their narrow leaves produced an open crown that was less damaged by typhoons. They were also suitable for producing round timber for local use and in the mines, and as a source of essential oils. *Eucalyptus botryoides*, *E. camaldulensis*, *E. exserta*, *E. globulus*, *E. maidenii*, *E. robusta* and *E. tereticornis* were common in ‘four-side’ plantings, with one species or another being favoured according to local climatic conditions (Chen 2002a).

Major progress was made in the 1980s by testing, in different environments, a large range of species and provenances of known origin. In 1985, the Ministry of Forestry’s new policy promoting ‘fast-growing, high-yielding’ plantations for timber production changed the management objective from a regime primarily producing mining timber to one directed at woodchips for pulp and paper, and reconstituted wood products such as medium-density fibreboard and particleboard. This change affected the choice of eucalypt species for planting. It was anticipated that the pulp plantations would be situated in the more coastal areas of Guangdong, Guangxi and Hainan, where most plantations were of *E. exserta* and *C. citriodora*. These species have a relatively high wood density that is less suitable for pulp than some other fast-growing species, such as *E. grandis* and *E. urophylla*, that were being grown for pulpwood in other countries. Some of these fast-growing species have high nutritional needs. In a 1983 trial at Dongmen, Guangxi, for example, *E. grandis*

was more productive than *E. exserta* when phosphate fertiliser was applied, but the reverse was true without phosphorus (Simpson 1999). Researchers had to factor this into their species/provenance testing and concurrently determine optimal levels of site management for general practice, especially fertiliser regimes.

From 1965 to 1983, the Dongmen State Forest Farm tested 57 species of eucalypts, but used only *E. exserta* and, to a lesser extent *C. citriodora*, in its plantations. The Australia–China project at Dongmen between 1983 and 1989 evaluated 38 species and 83 provenances with 5 fertiliser treatments in over 30 experiments (Wei 1996). The different fertiliser treatments enabled the species to be ranked for growth according to how much fertiliser they received. The screening trials included *E. urophylla* (12 provenances), *E. grandis* (11 provenances), *E. camaldulensis* (11 provenances), *E. tereticornis* (17 provenances), *E. cloeziana* (17 provenances) and *E. dunnii* (9 provenances). A particularly valuable introduction was the hybrid *E. grandis* × *E. urophylla* from Brazil, as it stimulated interest in eucalypt hybrid combinations, especially those involving *E. grandis* (Li et al. 2003a).

With the application of fertiliser, many species outperformed *E. exserta* and *C. citriodora*, with *E. urophylla* producing more than double the volume of *E. exserta* (Table 8). The highest mean annual increments recorded in individual trials were *E. urophylla* 30.4 m³/ha, *E. urophylla* × *E. grandis* 25.3 m³/ha and *E. cloeziana* 23.0 m³/ha. More recent data from a test of locally selected *E. grandis* × *E. urophylla* clones showed that this hybrid is more productive than any pure species at Dongmen. A 7-year-old plantation had an overbark mean annual increment of 35.3 m³/ha (R.E. Pegg, Forestry Consultant, pers. comm. 2006).

The Dongmen trials revealed great variation between provenances of some species in growth rate. In a 4-year-old trial of low-altitude provenances of *E. urophylla*, the best provenance produced 19.9 m³/ha/year and the poorest 13.6 m³/ha/year. Similarly, in a range-wide provenance trial of *E. cloeziana*, the volume production of the best provenance was 2.5 times that of the slowest-growing provenance (Wei 1996). Although the presence of high levels of genetic variation in some eucalypts was known from studies elsewhere, these results provided an indication of which provenances were best adapted to environmental conditions similar to those of Dongmen in southern China.

Research at Dongmen has established that *E. urophylla* (low-altitude provenances) and *E. urophylla* × *E. grandis* are highly productive at that site, followed by *E. grandis* (tropical provenances), *E. camaldulensis* (tropical provenances), *E. cloeziana* (coastal provenances) and *E. pellita* and that, with appropriate management, these species have the potential to be grown commercially on similar sites in southern China (Pegg and Wang 1994).

Eucalyptus cloeziana has denser wood than *E. urophylla* and its hybrids, and is less suitable for paper pulp plantations. The research also demonstrated that some eucalypts grew too slowly to be included in high-yielding plantations on sites similar to Dongmen, but that species such as *E. dunnii* would prove to be highly productive under different site conditions in China.

In 1986, 3 years after the Dongmen project started species/provenance trials in Guangxi, a complementary ACIAR research project to test a wide range of eucalypt species and provenances in a variety of environmental conditions in other provinces was begun. Trials were not established in Guangxi to avoid duplication with the Dongmen project. The project was able to draw heavily on the genetic resources of many eucalypts held by the CSIRO Australian Tree Seed Centre. The researchers used computer-aided climatic analysis techniques to match species with sites (Booth 1985; Yan et al. 1996). Australian scien-

tists provided additional suggestions, and assisted with experimental design and data analysis. Some 59 species comprising 246 provenances and 572 identified families were included in trials in provinces where an expansion of eucalypt plantations was planned (Bai 1994). From 1986 to 1988 a series of trials was established in Yunnan (high altitude, cool subtropical), Fujian (low altitude, warm subtropical), Guangdong (low altitude, tropical) and Hainan (low altitude, tropical, semiarid). At some of the trial sites, especially in Hainan, the frequency of typhoons was a significant factor. The trials covered 79 ha at 22 sites. The new genetic resources were compared with local selections in field trials on representative sites. Early growth data from small-plot trials were used as the basis for establishing larger areas of the most promising species and provenances to provide more reliable production data and as local sources of improved seed.

Many early results from the ACIAR trials were published in Boland (1989) and Brown (1994). Species trials were reported from Yunnan (Wang et al. 1989; Zheng et al. 1994), Hainan (Liang et al. 1994; Wu et al. 1994b), Guangdong (Wu et al. 1994a) and Fujian (Bai 1988). Provenance studies included *E. camaldulensis* (Liang et al. 1994; Wu et al. 1994b), *E. globulus* (Zang et al. 1995), *E. grandis* (Liang et al. 1994; Wang et al. 1994b), *E. nitens* (Wang et al. 1994c) and *E. tereticornis*

Table 8. Growth of introduced eucalypt species relative to *Eucalyptus exserta* at Dongmen

Species	Total volume mean annual increment (m ³ /ha/year) ^a	Improvement over <i>E. exserta</i> (%)
<i>E. urophylla</i>	24.3	134
<i>E. cloeziana</i>	21.4	106
<i>E. grandis</i> × <i>E. urophylla</i>	18.9	82
<i>E. grandis</i>	15.9	53
<i>E. propinqua</i> ^b	15.6	50
<i>E. tereticornis</i>	13.2	27
<i>E. pellita</i>	12.6	21
<i>E. camaldulensis</i>	11.5	11
<i>E. exserta</i>	10.4	0
<i>Corymbia citriodora</i>	10.2	-2

^a Fertiliser N₁₀₀P₅₀K₅₀ + trace elements mix. Volume = 0.42 basal area × predominant height.

^b Tested as *E. propinqua*, but probably *E. longirostrata*

Source: based on Simpson et al. (2003)

(Xu et al. 1994; Zhou and Liang 1994). The results confirmed that some of the new introductions were outperforming the local eucalypt land races, often doubling wood-volume production.

In the higher-rainfall areas of eastern Hainan, tropical provenances of *E. grandis*, *E. camaldulensis* and *E. tereticornis*, and low-altitude provenances of *E. urophylla* grew well. At 5 years of age, the estimated mean annual volume increments of the best provenances were 25.6 m³/ha/year for *E. urophylla*, 16.4 m³/ha/year for *E. grandis*, 15.6 m³/ha/year for *E. camaldulensis* and 14.8 m³/ha/year for *E. tereticornis*. These species/provenance trials were damaged by a severe typhoon in 1988, which event provided valuable information on the relative susceptibility of different species to strong winds. *Eucalyptus camaldulensis* and *E. tereticornis* proved to be most resistant to damage, much better than the local land races of *E. exserta* and *C. citriodora* and the very productive *E. urophylla* (Liang et al. 1994). On a much drier site in south-western Hainan, *E. urophylla* survived poorly, and tropical provenances of *E. camaldulensis* and *E. tereticornis* were the most productive (Wu et al. 1994b). Some of the best *E. tereticornis* provenances came from a zone of introgression between *E. camaldulensis* and *E. tereticornis* in northern Queensland. Material from this zone has now been designated *E. camaldulensis* ssp. *simulata*.

ACIAR-supported species trials on the south-western plateau (2000 m) in Yunnan identified some promising alternative species to the local land races of *E. globulus* and *E. maidenii*. At 4.5 years, *E. smithii*, *E. benthamii*, *E. badjensis*, *E. nitens* and *E. camphora* had greater volume production than *E. globulus* and *E. maidenii*. Although the trials were fertilised with nitrogen, phosphorus and potassium at planting, a complicating factor was an undiagnosed boron deficiency, a problem investigated at a later date in nutrition studies (Dell and Malajczuk 1994). In 1990, this series of trials also included species such as *E. regnans*, *E. elata*, *E. obliqua*, *E. fastigata*, *E. fraxinoides* and *E. pauciflora*, members of the subgenus *Monocalyptus* that have rarely been successful when planted outside Australia, and the successful growth of some of these species was of scientific interest (Wang et al. 1999).

In Yunnan, where farmers grow many eucalypts on a small scale, essential oils are an important product. Of the fast-growing species, *E. nitens* and *E. benthamii* were not suitable for oil production, but *E. smithii* gave

a relatively high yield of cineole. *Eucalyptus smithii* was therefore identified as having considerable potential for both oil and wood production in Yunnan and the adjoining provinces of Sichuan and Guizhou (Zheng et al. 1994; Wang and Zhou 1996; Wang et al. 2002). The ACIAR trials were complemented by progeny trials of 100 families established in Yunnan, Sichuan and Fujian in 1995 by CERC, with the cooperation of provincial forest researchers, to provide, after selection, a future source of improved seed (Chen 2002a). In 1997, the State Commission of Science and Technology approved a priority project to extend the planting of *E. smithii*, with the CAF Research Institute of Forestry assigned to provide technical support. In 2000–2003, with financial support from SFA, and the cooperation of the Forestry Institute of Chuxiong Prefecture and some forestry bureaus, over 3,000 ha of *E. smithii* plantations and seed-production areas were established in central Yunnan and parts of Sichuan. In these areas, farmers now prefer to plant *E. smithii* rather than *E. globulus* (Wang Huoran, Research Institute of Forestry, pers. comm. 2006).

A recent review of eucalypt performance in Yunnan confirms that *E. globulus*, *E. maidenii* and *E. smithii* have grown well on a range of sites, and that *E. badjensis*, *E. macarthurii* and selected provenances of *E. nitens* have shown sufficient promise to warrant further monitoring and testing (Arnold and Luo 2003). Eucalypt planting in south-central China has been mainly on a small scale to provide fuelwood, round timbers for local use and essential oils. *Eucalyptus saligna* and *E. dunnii* have been planted since 1998 in cooler, mountainous parts of north-western Fujian (van Bueren 2004).

Results of ACIAR species trials in Guangdong and southern Fujian were similar to those from the Dongmen trials in Guangxi, with *E. urophylla*, *E. urophylla* × *E. grandis*, *E. grandis* and *E. cloeziana* being superior to the local land races of *E. exserta* and *C. citriodora*. The ACIAR trials received varying levels of fertiliser, and so it was more difficult to compare growth between sites than between the trials at Dongmen. Researchers assessing both the ACIAR and the Dongmen species and provenance trials noted that the production ranking of different species changed over time and cautioned against drawing conclusions until at least half the estimated rotation age. However, by the mid 1990s, on the basis of the findings of the Dongmen and ACIAR trials, Bai (1994) and Wang and Zhou (1996) were able to recommend eucalypt species

for planting in different climatic regions of southern China. With longer-term observations and more recent selection and hybrid breeding, 18 superior species, including 63 provenances/families and clones, have been identified and used in large-scale plantations in tropical areas of southern China (Bai et al. 2003).

Tropical and subtropical eucalypts are not adapted to cooler, inland areas of south-central China and may be killed or severely damaged by low temperatures. Yunnan, Sichuan, Guizhou, Hunan, Jiangxi, Zhejiang and parts of Fujian and northern Guangxi are provinces where plantation development has the potential to proceed successfully if eucalypts tolerant of frosts were available. These provinces also face a range of other forestry and environmental problems, as deforestation and inappropriate land uses have resulted in serious soil erosion in the extensive red-soil complexes of the region. Some 50 million ha of, mostly degraded, red and yellow soils (Ferrosols and Argosols) have been proposed for afforestation with cold-tolerant eucalypts (Laffan et al. 2003). Although such action has been proposed for a number of years, the region was slow in adopting the science and technology of eucalypt plantations until about 2000. Since then, a number of eucalypt species, including *E. smithii*, *E. dunnii*, *E. saligna* and *E. benthamii*, have shown high potential in these areas and this has led to substantial plantation establishment programs in some of the cooler regions such as northern Guangxi, Hunan and inland Fujian (Arnold et al. 2004).

Eucalypt domestication in cooler regions of southern China was continued between 1999 and 2004 in another ACIAR project, 'Development of germplasm and production systems for cold-tolerant eucalypts for use in cool regions of southern China and Australia'. Collaborative research on species selection and other aspects of tree domestication, coordinated by CERC and CSIRO, took place in Fujian, Guangxi, Hunan and Yunnan. Results for Hunan, for example, are given by Lin et al. (2003) and, for Fujian, by Lan et al. (2003). This project took advantage of the significant genetic resources of *E. dunnii* and *E. grandis* provided earlier to CERC by AusAID. Results from a series of trials identified species with potential for planting on the high-altitude Yunnan plateau and on lower-altitude sites in Hunan, inland Fujian and northern Guangxi. The best species at higher altitudes were *E. globulus*, *E. maidenii* and *E. smithii*; at altitudes below 1000 m, *E. dunnii* and *E. saligna*; and, on milder sites, selected

provenances of *E. grandis* (Arnold et al. 2004). Selection of cold-tolerant species and provenances over the past 10 years has greatly extended the geographical range over which commercial eucalypt plantations can be potentially profitably grown in south-central China, but there is scope for further evaluation of some species.

Much of the progress made in species selection has been in projects involving international cooperation, but this should not overshadow the valuable work carried out independently by some of the national and provincial forest research institutes and universities, two examples of such being the selection of species and provenances with resistance to bacterial wilt (*Ralstonia solanacearum*) by the Department of Forestry, South China Agricultural University (Wu and Liang 1988) and cold-tolerant eucalypts trials in Fujian (Lan et al. 2003), Hunan (Liu et al. 2003) and Sichuan (Li and Hu 2003). Also, the China Eucalypt Research Centre has undertaken numerous independent studies, including testing selected eucalypts for higher-value wood products (Yang 2003).

Growing eucalypts to large diameter for use in furniture, shipbuilding and other high-value purposes is a recent activity. It requires a suite of species that may differ from those used for pulpwood; for example, higher basic density is acceptable, high levels of extractives are not a problem and red-coloured wood may be favoured. Provenance/family trials of a range of potentially valuable species in Fujian, Guangdong, Guangxi, Hainan, Hunan and Yunnan, have been established by CERC. The main species are *E. benthamii*, *E. camaldulensis*, *E. cloeziana*, *E. globulus*, *E. grandis*, *E. pellita*, *E. saligna* and *C. torelliana*, and the early results are promising (Yang 2003).

Tree breeding

The tree breeder is fortunate that forest trees are mostly wild populations, changed little by the actions of people and with a large store of genetic variability. The breeder must determine the extent of variability, isolate what is useful, package it in a desired tree and multiply it. These steps have been applied since about 1950 to the major plantation species in many countries. Eucalypt breeding in China started in the 1960s and 1970s when

researchers observed, in plantations, natural hybrids that were growing faster than surrounding trees. Of particular interest was a hybrid of *E. exserta* and *E. robusta* (?) designated *E. 'leizhou No. 1'* or *E. 'leilin No. 1'* by Leizhou Forestry Bureau. The open-pollinated progenies of this tree were planted out after selection of intermediate forms, based on seedling leaf width, in the nursery. Subsequently 4,680 'superior' trees were selected in the plantations for further breeding. Further artificial crosses of *E. exserta* and *E. 'leizhou No. 1'* were made (Mo 2003). In the 1960s, hybrids of *E. saligna* and *E. exserta* in Guangxi and *E. globulus* and *E. robusta* in Sichuan were observed (Wang 1991). An artificial hybrid of *E. saligna* and *E. exserta* proved to be fast growing in trials in eight provinces, and more than 1,000 ha were planted at Shankou Forest Farm, Hepu, Guangxi (Guangxi Research Institute of Forestry 1988).

Research on species and provenances in the 1980s, and the assembly of a large eucalypt gene pool, formed a basis for future genetic improvement of eucalypts through breeding in southern China. The efficient capture of genetic gains from breeding programs depends on the breeding strategy employed. The strategy needs to meet the objectives of the organisation, such as significantly increasing plantation productivity by achieving gains through selection for appropriate traits, including wood properties, while maintaining sufficient genetic diversity for continued improvement. Developing seed orchards to produce improved seed, or applying vegetative propagation techniques to multiply clones of outstanding individuals, are means of capturing genetic gains from breeding programs. Both pathways have been used in China to deploy improved genetic material into commercial plantations. Vegetative propagation is discussed further under 'Nursery practices'.

Breeding strategies were prepared for *E. camaldulensis*, *E. grandis*, *E. tereticornis* and *E. urophylla* by Nikles (1987) for the Dongmen project, for *E. globulus* by Raymond (1988) in the ACIAR project and more generally for tree improvement of eucalypts in southern China by Eldridge (1991) for the NAP. Breeding plans were prepared for *E. globulus*, *E. maidenii* and *E. smithii* in Yunnan, and for *E. dunnii* in Guangxi, *E. saligna* in Hunan and *E. grandis* in Fujian between 1999 and 2004, as part an ACIAR project on cold-tolerant eucalypts in south-central China (van Bueren 2004).

The breeding strategies include both short- and long-term activities. Short-term activities include the development of seed production areas to deliver slightly improved seed by thinning existing plantations and making selections of individual trees within plantations to create breeding populations. Longer-term strategies at Dongmen included the setting up of clonal areas for testing clones for rooting ability, growth rate and wood density, using selected clones in controlled hybridisation and seed collection. Family trials were also promoted to broaden the genetic base of the targeted species. Clonal multiplication banks, clonal block tests, hybrid breeding (the crossing of selected individuals), and yield trials were established to compare the best seed sources with the best clones. Research on wood characteristics for breeding is discussed under 'Wood quality'.

Initial progress at Dongmen was described by Wei (1996). Some 45 ha of seed production areas were developed of the major species, including 30 ha of *E. urophylla*. By 1993, 400 kg of seed had been harvested from the *E. urophylla*. Over 1,000 families of 6 species were included in family trials and some of these trials were converted into seedling seed orchards. In addition, 5 ha of clonal seed orchards of selected trees of *E. camaldulensis*, *E. grandis*, *E. tereticornis* and *E. urophylla* were established to test the clones, provide high-quality seeds of each species, and to produce F1 hybrid seed.

The first hybrid of *E. grandis* × *E. urophylla* was introduced into Dongmen from Brazil and planted in 1984. More hybrids, including *E. grandis* × *E. robusta*, were introduced from Florida in 1985. The excellent growth rate of the hybrids, over 20 m³/ha/year, encouraged development of a hybridisation program (Wei 1996). Controlled pollinations began in 1986 and 1,207 crosses were made of *E. camaldulensis*, *E. grandis*, *E. tereticornis* and *E. urophylla*, *E. exserta*, *E. 'leizhou No. 1'*, *E. robusta*, *E. brassiana* and *E. grandis* × *E. urophylla*. Hybrid trials covering 14 ha were planted between 1988 and 1991. More than 850 tree selections of *E. camaldulensis*, *E. grandis*, *E. tereticornis* and *E. urophylla* and *E. grandis* × *E. urophylla* were made in the Dongmen trials and plantations, and from these selections came the majority of parents of the hybrid clones currently deployed in China. Of particular interest is clone U6, sometimes called 'Zhanjiang U6', which is widely planted in southern China. It is a natural hybrid between *E. urophylla* and *E. tereticornis* selected by Zhanjiang Forest Bureau in a plantation of *E. urophylla* raised from

Dongmen seed. There have been further selections by some farmers of progeny raised from seed collected in U6 plantations (R.E. Pegg, forestry consultant, pers. comm. 2005, 2006).

'Demonstration' plantations of high-yielding clones have been established and intensively managed on sites with above-average soils in Guangxi, Guangdong and Hainan provinces. They are not typical of average plantations, but do illustrate the potential growth of eucalypts. A demonstration plantation of a *E. urophylla* × *E. grandis* hybrid clone (clone DH32-29 originating from Dongmen Forest Farm) planted on a basalt-derived soil in Hainan is reported to have had a mean annual increment of 67 m³/ha/year at age 5 years (R.E. Pegg, forestry consultant, pers. comm., in Arnold (2005)).

The Research Institute of Tropical Forestry has maintained a eucalypt tree improvement program including species/provenance trials, family trials, seed orchards, hybridisation and breeding biotechnology. Substantial variation in growth rate and wood properties among families of *E. urophylla* and *E. tereticornis* grown at Yangxi County, Guangdong has been reported (Bai et al. 2003; Xu et al. 2003a); for example, estimated gains in volume at age 7 years of up to 18% by selecting the best 20% of families from an *E. tereticornis* provenance-family trial (Xu et al. 2003b). Breeding populations and seedling seed orchards of tropical eucalypts have been established in Guangdong and Hainan. The RITF has made 1,760 intraspecific and interspecific combinations of *E. camaldulensis*, *E. grandis*, *E. tereticornis* (including *E.* '12 ABL') and *E. urophylla*, and 270 hybrid progenies have been tested in trials in Guangdong, Hainan, Fujian and Jiangxi provinces. Clones with the highest productivities have a mean annual increment of 47 m³/ha/year at age 3 years (Bai et al. 2003).

The benefits of seed orchards are demonstrated in a study by the Forestry College, South China Agricultural University and Leizhou Forestry Bureau of the progeny of a seed orchard of *E. urophylla* in Guangdong. Compared with progeny from a seed stand and imported commercial seedlots, genetic gains in individual tree volume for the progeny of the unrogued seedling seed orchard were 5.2% and 16.1%, respectively. For an advanced seed orchard established with superior selected trees, the estimated gains would be 10.4% and 31.3% (Huang et al. 2003).

Breeding progress with the cold-tolerant eucalypts has been slower than with the tropical species. Breeding research began in Yunnan in 1990 when the CAF Research Institute of Forestry organised a large progeny trial of *E. globulus* to provide a broad genetic base for a seed orchard and to compare the local land race with introduced material. The trial included 270 families from natural stands in Australia, seed orchards in Australia, New Zealand and Portugal, and the local land race (Zang et al. 1995). Genetic studies using a complete diallel mating design by the Yunnan Academy of Forestry have enabled breeding strategies for *E. globulus* and *E. maidenii* to be formulated with greater confidence (Li et al. 2003b,c).

Building on previous research by the Research Institute of Forestry and CERC, an ACIAR project, coordinated in China by CERC between 1999 and 2004, established 10 species/provenance/family trials to form the basis for seedling seed orchards of *E. globulus*, *E. maidenii*, *E. smithii* and *E. dunnii* in Yunnan, Guangxi, Hunan and Fujian (van Bueren 2004). Fujian now has clonal and seedling seed orchards of *E. grandis* and some partially tested clones available (R. Arnold, RGM/APRIL, pers. comm. 2006).

Most of the tree selection and breeding in China has followed conventional procedures, and there is increasing emphasis on wood quality and disease resistance. There is now interest in complementing conventional technologies with new molecular technologies such as gene transfer and molecular markers. At RITF, researchers have used RAPD markers to develop linkage maps of *E. urophylla* and *E. tereticornis* (Bai et al. 2003; Gan et al. 2003). CERC, in collaboration with the Chinese Academy of Agricultural Sciences, is using gene transfer and molecular markers to produce material resistant to the bacterial wilt disease *Ralstonia solanacearum* (Mo 2003). CSIRO Forestry and Forest Products in Canberra has, since 2001, hosted three Chinese postdoctoral scientists from RITF and the Research Institute of Forestry. These scientists have participated in gene discovery and genetic mapping on eucalypts under the direction of senior Australian scientists. Their research has been aimed at identifying genes controlling wood fibre development in eucalypts (S. Southerton, CSIRO, pers. comm. 2006).

Groups such as Leizhou Forestry Bureau, Dongmen State Forest Farm and Guangxi Forest Research Institute, CERC and RITF were early leaders in eucalypt breeding in China. More recently, Qinzhou Prefecture Forestry Institute and Bobai Forest Farm in Guangxi have invested in tree breeding and clone production. Many other institutions are also engaged in eucalypt population improvement programs to a greater or lesser extent. They include universities, provincial forestry bureaus and research institutes, county/city forestry bureaus and research institutes, and individual forest farms. Foreign companies with eucalypt investments in China have also initiated tree-improvement work. With few exceptions, these diverse but related improvement programs have remained separate, with no coordination and little interchange of knowledge and materials (UNDP 2006). To alleviate this situation, it has been suggested that an efficient way forward would be to initiate formal cooperation by establishing a breeding cooperative for key eucalypt species (Arnold 2005). Tree breeding cooperatives have operated successfully in other countries for many years and such cooperation could further improve eucalypt plantation productivity in China. However, with so many commercial interests involved, implementation of such a cooperative will be a major challenge.

Nursery practices

When plantation managers can be certain that each seedling or rooted cutting they plant will produce a tree with the desired characteristics and have a very high probability of survival, they can adjust their silvicultural practices of spacing, nutrition and thinning to maximise growth on fewer trees. This can reduce plantation costs, increase productivity and ensure that the potential gains from tree breeding are realised. Nursery practice therefore should aim to produce sufficient quantities of sturdy, vigorous plants with high survival and growth potential (McGuire et al. 1988). One of the key objectives of the NAP (1990–1997) was to improve the quality of the 1.39 million ha of forest plantations planted in the project, through the use of superior planting stock and by introducing improved techniques of plantation establishment and intensive management.

Standard nursery techniques for raising eucalypt seedlings in southern China until the early 1980s were designed to raise seedlings at low cost and with minimal use of imported materials. A common practice was to germinate seeds broadcast on a specially prepared seedling bed and then transplant small seedlings at the 4–6 leaf-pair stage into another bed where the soil had been prepared to a consistency such that it could be cut into blocks. Alternatively, the seeds were sown directly into a depression in the centre of the earth block, covered with fine soil, and thinned to two seedlings per block at the two-leaf-pair stage (Turnbull 1981). The block (brick) system did not promote lateral root development and, when the bricks were left in situ in the nursery, large sinker roots developed that were broken when the plants were transferred to the field. Survival in plantations was often low (Wang and Zhou 1996). The brick system was reasonably effective for hardy species such as *E. exserta* and *C. citriodora*, but wasteful of seed. Research at Dongmen found that *E. camaldulensis* and *E. tereticornis* could be raised by this method, but it was not suitable for more sensitive species such as *E. cloeziana* (McGuire et al. 1988).

The Dongmen project introduced new techniques and refined existing nursery practices. These included (McGuire et al. 1988):

- delaying sowing according to germination and growth information to ensure seedlings were of optimal size at the time of planting out
- transplanting from germination trays at an early stage before extensive roots developed
- using plastic containers and carrying trays to facilitate root pruning and easy transport of seedling in the nursery and to the field
- shading transplanted seedlings
- foliar application of fertilisers, fungicides and insecticides.

Wang and Zhou (1996) suggest that eucalypt seedling propagation practices improved generally after the techniques developed at Dongmen were publicised by Mo (1989).

In the 1990s, container systems came into general use, soil mixes were refined and liquid fertilisers applied weekly (Wang and Zhou 1996). Seedlings were initially raised in soil-filled polybags. The bags could be manufactured locally and were inexpensive, but had a number of disadvantages. They required large amounts of soil, were poorly aerated and often waterlogged, were not reusable and, importantly, often produced seedlings with poor-quality root systems. The benefits of more modern nursery practices including lighter, smaller containers that were designed to prevent root twisting, improved potting media, and the potential for inoculating seedlings with mycorrhizas in the nursery and field were highlighted in an ACIAR-sponsored international training workshop held at Kaiping, Guangdong, in 1994 (Brundrett et al. 1995). Following this workshop, a comprehensive manual was published to further extend improved nursery practices (Brundrett et al. 1996). The potting medium used depended very much on what was available locally, but standards for container sizes and seedling development were determined by organisations such as the Leizhou Forestry Bureau and Yunnan Academy of Forestry (Chen 2002a).

Interest in vegetatively propagating eucalypts began in the 1970s when fast-growing natural hybrids were observed in plantations. The first commercial clonal forest plantations used rooted stem cuttings (macro-cuttings) taken from stool beds of selected clones. Micro-cuttings obtained from tissue culture in vitro have been used and, more recently, a system of vegetative propagation ex vitro based on mini-propagules, termed 'mini-cuttings', has been developed, and field clonal hedges are being replaced by indoor mini-hedges using hydroponics (Evans and Turnbull 2004). Many of these techniques have already been applied in China, although the mini-cutting system has yet to be implemented.

Leizhou Forestry Bureau attempted as early as 1978 to mass-produce a superior clone of *E. leizhou* No. 1, but results were unsatisfactory. In 1974, researchers in the Congo and Brazil developed vegetative propagation techniques that allowed the development of clonal plantations using hybrid combinations. Aware of these developments, Australian researchers began vegetative propagation research in 1983 at Dongmen, concentrating on the most promising species and selected hybrid families. A visit in 1987 by Brazilian expert

Edgard Campinhos, facilitated the introduction of new techniques for vegetative propagation of eucalypts at Dongmen and elsewhere in China. Perkins and Xiang (1988) described techniques used at Dongmen. In 1993, 400 ha of clonal eucalypt plantations had been established at Dongmen, and clones were gradually replacing seedlings in plantations (Wei 1996). Dongmen now produces about 15 million cuttings each year (D.G. Nikles, Department of Primary Industries and Fisheries, Queensland, pers. comm. 2006). Some of the clones produced by researchers at Dongmen are being used in neighbouring Laos and Vietnam (S.J. Midgley, Salwood Asia Pacific, pers. comm. 2006).

Research stations in Guangdong, Guangxi and Hainan developed techniques for vegetatively propagating eucalypts by tissue culture and cuttings, but initially there were problems with the quality and quantity of the planting stock (Bai 1994). Collaboration between Leizhou Forestry Bureau and Guangdong Forestry Research Institute in 1990 resulted in an effective tissue-culture technology. Since then, Leizhou Forestry Bureau has used the technology to propagate 200 clones of 11 eucalypt species, and it has a facility capable of producing one million clonal plants annually (Mo 2003). In Guangxi, the Qinzhou Prefecture Forestry Institute produced 260,000 tissue-cultured plants in 1989 and most were planted out (Wang 1991). A tissue-culture unit was set up at Dongmen in 1993 with the objective of producing a minimum of one million plants annually (Wei 1996). Cuttings taken from micropropagated juvenile plants ex vitro improved the mass propagation of selected trees and, in 1991, over three million cuttings of *E. urophylla* × *E. grandis* were produced (Wang and Zhou 1996).

China's State Planning and Development Commission and SFA have made major investments since 1998 to improve the quality of seedling for plantations. Modern nurseries have been developed in southern China with the capacity to produce high-quality seedlings and cuttings and, by 2003, six nurseries were producing more than 10 million cuttings of eucalypt hybrid clones annually (Bai et al. 2003). The Southern State Tree Seed and Seedling Demonstration Base in Zhanjiang, Guangdong, was opened in 2003. This nursery is highly automated and designed with a capacity to produce up to 40 million rooted eucalypt cuttings/seedlings annually (Mo 2003). It is the largest facility of its kind in China. However, there are still numerous small

nurseries producing rooted cuttings of easily rooted clones with much labour and minimal equipment. They service many private and small-scale growers and are frequently sited beside roads in parts of southern Guangxi and western Guangdong.

The substantial investment in tree breeding since the late 1980s has produced a considerable number of fast-growing hybrid clones, including *E. urophylla* × *E. tereticornis*, *E. urophylla* × *E. camaldulensis*, and *E. grandis* × *E. camaldulensis*. Superior clones of *E. urophylla* and *E. urophylla* × *E. grandis* have been developed at Dongmen, Guangxi Forest Research Institute and Zhanjiang Forestry Bureau (Figure 9). However, very large areas of eucalypt clonal plantations being established in Guangdong, Guangxi and Hainan have a narrow genetic base (R.E. Pegg, forestry consultant, pers. comm. 2006). Possibly over 90% of commercial plantations in these provinces are established with

around 7–10 clones of combinations of *E. grandis* and *E. urophylla*, and a total of only about 20 clones may have been used in commercial plantations in the whole country (Wang Huoran, Research Institute of Forestry, pers. comm. 2006). Barr and Cossalter (2004) claim that only three clones, i.e. U6 (*E. urophylla* × *E. tereticornis*), W5 (*E. '12 ABL'*) and *E. 'leizhou No. 1'* are used in about 90% of the plantations in western Guangdong. There is concern that the rapid expansion of plantations over several provinces has not been supported by the deployment of new clones tested for superior growth and resistance to pests and diseases. The lack of genetic diversity and the failure to deploy new clones are regarded as significant risks to the sustainability of the plantations. A factor contributing to this situation may be that nursery managers often resist the introduction of new clones whose nursery performance is less well known because of their potential effect on total production costs (MacRae 2003).



Figure 9. Clonal planting of a hybrid eucalypt for pulpwood production at Pu Bei county, Qinzhou prefecture, Guangxi. Planting distance 4 m × 1.25 m. Expected mean annual increment at end of rotation (6 years) is 26 m³/ha/year. [C. Cossalter]

Silvicultural practices

Site preparation

Countries that have the highly productive eucalypt plantations are aware of the benefits of optimal soil preparation practices. Intensive cultivation practices, including burning of plant residues, ploughing and harrowing, prevalent in Brazil in the 1970s and 1980s, have in the past 10 years given way to 'minimum cultivation' techniques that involve disturbing the soil only to the extent necessary, retaining organic residues and using herbicides to control invasive weeds (Evans and Turnbull 2004). Site preparation practices for eucalypt plantations have also evolved in China.

Until 1974, planting sites at Dongmen were ploughed once, and either spot cultivated or not cultivated at all. After 1974, relatively level sites were cultivated to a fine tilth. Site preparation involved removing any stumps and levelling of erosion channels, two chisel ploughings and up to six passes with mouldboard and offset disc ploughs (McGuire et al. 1988). On steep slopes, pits were dug and usually planted with *Pinus* spp. In places where tractors and ploughs were not available, eucalypts were planted in trenches.

Very intensive mechanical site preparation is expensive and has a number of negative environmental effects. Removal of nutrients during harvesting or removing stumps and existing ground vegetation and litter can result in major nutrient losses; and preparing the soil to a fine tilth exposes the site to accelerated erosion. For these reasons, the Dongmen project tested a range of site preparation and fertiliser options in 1984 and 1985. The results indicated that, with less intensive site preparation and the addition of fertiliser, significant economies were possible in plantation establishment costs, site productivity could be increased and erosion minimised (Stevens 1986; McGuire et al. 1988; Wei 1996). The trials showed that:

- pit planting was inferior to other forms of cultivation
- excessive cultivation reduced tree growth, possibly due to mineralisation and leaching of nutrients
- deep cultivation had no benefits over traditional cultivation methods

- stricter weed control was necessary with lesser levels of cultivation
- the high costs and large soil disturbance of stump removal were not justified
- the best economic treatment without stumping was one pass of a winged ripper between the stumps.

An integrated site-preparation plan prepared for Dongmen that featured three cultivation types (overall ploughing, strip ploughing and terracing) according to slope on well-drained land, and high mounding on poorly drained sites, was not popular with plantation managers because of its complexity in planning and implementation. Currently, sites at Dongmen are prepared by one pass with rock rippers and one offset pass with a winged ripper to give adequate vertical cultivation with minimal disturbance of the soil surface (R.E. Pegg, forestry consultant, pers. comm. 2005).

In Yunnan province, where planting sites are often steep and/or stony, complete cultivation is often impractical, and the normal practice is to plant into a pit in a pre-prepared trench 60 cm deep and 60–80 cm wide along the contour. When mechanical cultivation is possible, the whole area is ploughed to a depth of 30 cm (Wang and Zhou 1996; Chen 2002a). Pit planting is still used elsewhere in southern China when eucalypts are planted in hilly country. Commonly, benches are cut on the contour and pits about 50 × 50 × 35 cm prepared manually.

Laffan et al. (2003) recommended management practices to minimise erosion and landslide risks in plantations developed on the red and yellow soils in Yunnan, Guangxi, Hunan and Fujian. They included spot cultivation rather than terracing during site preparation, establishing protective ground vegetation on terraced lands, and careful attention to the siting of roads and drains.

Current site preparation practices in Guangdong, Guangxi and Hainan are still quite intensive, with ripping, ploughing to a depth of 30 cm and harrowing, followed by digging of planting holes 30 × 30 × 30 cm (Chen 2002a). Serious soil erosion, associated loss of nutrients and reduced soil organic matter contributes to low plantation productivity and remains a concern. Research to overcome these problems, and to develop options for site-management practices that will sustain

or improve productivity of eucalypt plantations over successive rotations in southern China, is in progress as part of an international partnership project supported by CIFOR since 1996. Based on results for a plantation of *E. urophylla*, it has been recommended that operational practices for eucalypt plantations include harvest residue retention, adequate fertilisation and coppice regeneration (Xu et al. 2004).

Establishment spacing

Optimal spacing between trees in a plantation depends on a number of factors, including species' growth characteristics, site quality, need for machine access for tending and other operations, planned thinning regime and end use of the trees. Wider spacing has become more common as improved establishment practices have ensured better survival and selected germplasm has produced more acceptable trees. Spacing has little effect on height growth but a significant effect on stem diameter.

In the 1950s, some eucalypt plantations were densely stocked, with *E. globulus* in Yunnan as close as 0.5×1.0 m (20,000 stems/ha), although in the early 1960s wider spacing of 2.0×2.0 m (2,500 stems/ha) was becoming common (Richardson 1966). Even today, some plantations of *E. globulus* and *E. maidenii* in Yunnan, where essential oil is the primary product, have a stocking of 5,000 stems/ha (Chen 2002a), although more normal planting is 2.0×2.0 m (2,500 stems/ha) or 3.0×1.0 m (3,330 stems/ha) (Wang 1991).

Before 1980, in Guangdong and Guangxi, *E. exserta* was commonly planted at 3,750–4,500 stems/ha and *C. citriodora* at 2,250 stems/ha (Turnbull 1981). At that time, plantations at Dongmen had stocking densities ranging from 4,350 stems/ha (2.3×1.0 m) to 1,670 stems/ha (3.0×2.0 m) (R. E. Pegg, forestry consultant, pers. comm. 2005). Results from spacing trials at Dongmen in 1984–1985 suggested a stocking density of 1,000–2,000 stems/ha for *E. grandis* and *E. camaldulensis* (Wei 1996).

Currently, eucalypts in Guangdong and Guangxi are commonly planted at 1,600–2,200 stems/ha, although Leizhou Forestry Bureau plantations are at 2,000–3,333 stems/ha depending on clone and site type. Research indicates that maximum merchantable volume is achieved in the range 1,300–2,200 stems/ha (R.E. Pegg, forestry consultant, pers. comm. 2005), but Stora Enso plantations will have a spacing of 4.0×2.0 m, a density

of 1,250 stems/ha, which is consistent with practices in Australia, Brazil and South Africa. This spacing will permit access by mechanical harvesting at the end of the rotation if required (UNDP 2006).

Close spacing of trees in plantations in typhoon-prone areas, such as Leizhou Peninsula and Hainan Island, is based on the assertion that closely spaced trees have smaller crowns and hence better wind tolerance. Widely spaced young plantations planted at 3.0×3.0 m (1,110 stems/ha) or 3.0×2.5 m (1,330 stems/ha) suffer heavy losses in typhoons (Chen 2002b). Leizhou Forestry Bureau deploys a number of clones, including U6 (*E. urophylla* hybrid) and W5 (*E. '12 ABL'*), that have been selected for wind tolerance (Mo 2003).

Nutrient management

Many of the areas planted with eucalypts in southern China are on sites that have been degraded by erosion. Most of the soils are lateritic red earths (Oxisols or Ultisols) that are acidic, highly leached and deeply weathered. They are low in organic matter, so nitrogen is limited, and deficient in available phosphorus, potassium and some micronutrients such as boron (Dell et al. 2003; Simpson et al. 2003; Xu and Dell 2003). Most of the earliest eucalypt plantations were established with little or no fertiliser. Inorganic fertilisers were in short supply in China and, if fertiliser was used in forestry, it was usually organic material (Richardson 1966). Before 1974, the eucalypt plantations at Dongmen received no fertiliser; subsequently, a mixture of calcium magnesium phosphate and burnt soil (top soil and litter) was applied to some plantings. In the Leizhou Forestry Bureau plantations, 3–4 kg of animal manure or vegetable matter was applied in each hole before planting (Turnbull 1981). The levels of nutrients applied were generally insufficient to correct deficiencies and to significantly raise low productivity.

Until at least the mid-1980s, there was, in southern China, a lack of expertise on forest soils and tree nutrition. Researchers faced many constraints, and research support in this area by national and provincial institutes was consequently very weak (ACIAR 1986). Improvement of tree nutrition research to raise plantation productivity was an objective of the Dongmen State Forest Farm Eucalypt Afforestation Project (1981–1989) under the Australia–China Program of Technical Cooperation, and the assistance

provided included development of a soil and plant analysis laboratory and training of staff at the Guangxi Forest Research Institute to serve regional forestry requirements (Cameron et al. 1988). Australian and Chinese project staff and consultants also established many experiments at Dongmen to assess species/provenance by fertiliser interactions. There was a major response to fertilising with inorganic fertilisers in all species (Simpson 1999; Simpson et al. 2003).

The Dongmen results have been summarised by Wei (1996) and Simpson et al. (2003), with a warning of the need for caution in extrapolating the results from limited trials and single sites.

- The largest fertiliser response was to $N_{100} P_{50} K_{50}$ (where the subscripts indicate elemental kg/ha) and a mix of micronutrients including Mg, Mn, Mo, Cu, Zn and B.
- Application of a fertiliser containing $N_{100} P_{50} K_{50}$ at planting was sufficient to give a good initial growth response.
- All species tested responded positively to the $N_{100} P_{50} K_{50}$ fertiliser treatment, but the degree of response varied between experiments and species, being greater in *E. urophylla*, *E. grandis* × *E. urophylla* and *E. cloeziana*. Overall, the mean annual volume response of these taxa averaged 6.1 m³/ha/year.
- Combinations of N, P and K were better than any of these elements alone.
- There was a trend for fertiliser response to decline with time, and additional fertilising after 2–3 years may be beneficial.
- Foliar nutrient data are a useful aid in interpreting fertiliser responses, but do have limitations and are less useful for *Eucalyptus* spp. than for *Pinus* spp.

Rigorous scientific research into eucalypt nutrition at Dongmen provided good evidence of the benefits of fertiliser application on the early growth of eucalypts, and helped to change the perceptions and practices in Guangxi and Guangdong (Wei 1996).

During the 1990s, ACIAR supported research on eucalypt nutrition. The major project was 'Increasing productivity of eucalypt plantations in China by inoculation with ectomycorrhizas and nutrient application'

(1991–1998), and most of the field studies were in Guangdong and Yunnan provinces (Figures 10 and 11). The project investigated the problem of macronutrient and micronutrient deficiencies in eucalypt plantations in China and the role of mycorrhizal fungi in increasing seedling survival and plantation productivity (Malajczuk et al. 1994).

The main outputs of the research (van Bueren 2004) were:

- identification of site factors determining mycorrhizal responses and nutrient interactions
- development of molecular techniques for confirming the presence of some introduced fungi on tree roots in the field
- development of recommendations for macro- and micronutrient fertilisers for eucalypts.



Figure 10. Poor growth of *Eucalyptus globulus* due to nutrient deficiency in plantations at An Lin Forest Bureau, Yunnan. Trees in the foreground are unfertilised, while those in the background have received phosphorus and boron fertiliser. [J. Turnbull]

Research on micronutrient deficiencies was probably the most significant, as the capacity of micronutrients to limit productivity in eucalypt plantations had not previously been recognised adequately. In Yunnan, dieback of *E. globulus* was often attributed to frost damage or drought stress, but it is now known that, in this province, B may be the primary nutrient limiting eucalypt growth and resulting in dieback (Xu and Dell 2003).

Research conducted in and after the ACIAR project has produced reliable data on the requirements of trees for the micronutrients B, copper (Cu), iron (Fe), manganese (Mn) and zinc (Zn) in the years immediately following planting, and corrective fertiliser schedules are now available for many soil types (Dell et al. 2003). A manual illustrating nutrient disorders in plantation eucalypts, much of it based on research in China, and prescriptions for foliar analysis, has been produced by Dell et al. (2001). Some companies planting eucalypts in southern China are routinely using foliar analysis to determine nutrients limiting tree growth.



Figure 11. A fertiliser trial in a clonal planting of *E. urophylla* × *E. grandis* aged 25 months at Zhenghai State Forest Farm, Guangdong [J. Turnbull]

Recognising the very low P status of soils in southern China and the absence of symbiotic fungi normally associated with eucalypts in their native habitat, the ACIAR project aimed to identify strains of ectomycorrhizas that would improve the growth of eucalypts on nutrient-deficient sites. Research on ectomycorrhizas suggested that inoculated seedlings had improved survival and better growth in the first two years after planting. It is claimed that, on some sites, mean annual volume increments increased by 10 m³/ha/year using inoculated seedlings (Dell 2004; quoted in van Bueren (2004)). However, most isolates of ectomycorrhizal fungi have proved ineffective in increasing plantation productivity in field trials, possibly due to inappropriate nursery practices and poor fungal persistence after planting out (Xu and Dell 2003). These authors suggest further research is needed to determine the impact of P fertilisation on mycorrhizal effectiveness and to identify superior isolates for commercial use. Currently, it is not general practice to inoculate seedlings with ectomycorrhizas (Wang Huoran, CAF Research Institute of Forestry, Beijing, pers. comm. 2006).

Nutrient management in eucalypt plantations has been reviewed by Xu and Dell (2003). They concluded that:

- P is the primary macronutrient limiting eucalypt growth in southern China and is essential to sustain fast-growing plantations
- N fertilisation has improved tree growth, especially on sites low in organic matter and where there are competing weeds
- slash retention may improve the status of soil organic matter in second-rotation crops but, if the slash is removed, N fertilisation may be required
- positive responses to K fertilisation have been demonstrated only occasionally in first-rotation plantations, but any depletion of K could cause a problem in subsequent rotations
- B deficiency can be a problem, especially on eroded, sandy or granite-derived soils
- mean annual increments of up to 20 m³/ha/year can readily be achieved with better nutrient management.

A study to correlate eucalypt growth, nutrition and soil nutrient availability in the cooler areas of Yunnan, Guangxi, Hunan and Fujian provinces was carried out as part of the ACIAR project 'Development of germplasm and production systems for cold-tolerant eucalypts for use in cool regions of southern China and Australia' (1999–2003). It was concluded that there are relatively widespread deficiencies of N, P, K, B and Cu, and that fertiliser application is necessary to achieve economically successful establishment. It was suggested that site-specific N and P fertiliser prescriptions could be developed to accommodate the relatively wide range of N and P in soils at different locations (Baker et al. 2003).

Inorganic fertilisers are now commonly used in commercial eucalypt plantations in southern China, but rates of P application are low and knowledge of the effects of P application on nutrient utilisation by eucalypt plantations is limited (Xu et al. 2002). Some plantation managers, however, apply greater levels of some macronutrients at planting than the N₁₀₀ P₅₀ K₅₀ recommended for Dongmen (R.E. Pegg, forestry consultant, pers. comm. 2005). Applying fertiliser is expensive, so there is a strong case for research to develop optimal fertiliser prescriptions.

Apart from developing prescriptions for the effective use of inorganic fertilisers, there has been research to find ways of maintaining soil fertility by biological means. These include the use of nitrogen-fixing trees or shrubs, especially *Acacia* spp., planted in mixtures with eucalypts. Leizhou Forestry Bureau began mixed-species trials before 1980. This bureau has also cooperated with the South China Agricultural University and the Guangdong Ecology and Soil Institute on studies of the role of nitrogen fixation in plantations and the possibility of cultivating understorey cover crops such as grasses and green soybeans (Mo 2003). The effects of interplanting *E. urophylla* with *Acacia holosericea* have also been studied. The presence of the acacia did not initially improve the growth of the eucalypt, but there was a benefit in the latter stages of the second rotation, suggesting eucalypt–acacia mixtures could be beneficial in longer rotations (Xu et al. 2004). More research is needed to develop effective and economic ways to maintain soil fertility in eucalypt plantations by these biological interventions.

Weed control

Weeds compete with trees for moisture, nutrients and light and, if not controlled, can lead to seedling death or reduced growth. Nearly all plantations require some weeding during the first few years, until the trees close canopy and suppress competing weeds. Weed control is a vital part of successful eucalypt silviculture, as eucalypts are sensitive to competition. The intensity of optimal weed control varies between species, sites and climate. Early growth rate, onset of canopy closure and crown density will determine how long weeding needs to continue. Full weed suppression may never occur under species with light crowns, such as *E. camaldulensis*, and weeding may have to be carried out throughout the rotation.

Many sites used for eucalypt plantations in southern China are severely degraded and support little weed growth. Weeds were not a major problem in early plantations, as intensive site cultivation, dense planting and the ongoing removal of litter and ground vegetation for off-site use removed most competing weeds. In recent years, attention to weed control has become more critical with the introduction of new site-management practices, such as minimum disturbance of the soil surface, retention of slash, and fertiliser application, all of which may favour weed growth (Xu et al. 2004). There has been a trend to retain some weeds to increase the biodiversity in eucalypt plantations but this practice is likely to reduce productivity.

Some commercial operations in China control weeds mechanically, by ploughing and harrowing before planting and subsequently as needed. This may be supplemented with hand weeding around the trees (Chen 2002a). This approach is falling into disfavour, especially on soils with high potential erodibility and where high rainfall intensity increases the risks of severe soil erosion. In other countries, it is common to use both mechanical and chemical methods to control weeds before planting and, after planting, until crown closure. Weed control using glyphosate or similar chemicals is becoming increasingly important. Interest is growing in the use of chemicals for weed control in China. A 'no-burning site preparation' technique successfully used herbicide rather than burning to control vegetation before planting (Xie 2003). Ensuring the safe use of herbicides in forestry plantations is one of the greatest management challenges (Evans and

Turnbull 2004). There is some recognition of this in China. Guidelines for the use of herbicides Stora Enso's Management Plan, for example, respect workers safety and environmental needs (UNDP 2006).

Wood quality

When the Ministry of Forestry introduced, in 1985, a new policy promoting 'fast-growing, high-yielding' plantations for timber production, the management objective changed from a regime primarily producing fuelwood, poles and mining timber to woodchips for pulp and paper and other reconstituted wood products. This change of policy affected the choice of eucalypt species for planting, and interest in planting fast-growing species with wood properties suitable for paper pulp increased.

When tree-breeding strategies were developed for eucalypts in China in the late 1980s it was important to include wood properties in the selection criteria. This had already been demonstrated in Brazil, where clones were eliminated from plantation programs if their wood properties were not suitable for producing bleached pulp, and the result was a significant increase in pulp yields (Campinhos 1999). In 1988, a program was started to test the wood quality of all plus trees in the tree-breeding program at Dongmen, with the objective of selecting trees with wood suitable for kraft pulp and paper. A wood-technology laboratory was established and trees of several species were assessed. Those with a basic density in the range 480–570 kg/m³, late heartwood development, low extractive content and low bark-to-wood ratio were favoured (Harding et al. 1988). Basic density can vary greatly between provenances and families within provenances, and this has remained an important selection criterion (see, for example, Luo (2003)). Wood samples of eight species were sent from Dongmen to Australia and papermaking tests were carried out on unbleached and bleached kraft pulps produced from them (Phillips 1991).

Most eucalypt plantations are grown on a rotation of 3–7 years and harvested for pulpwood, veneer logs and other small-size material. There has been limited production of sawlogs on longer rotations, although, for example, Leizhou Forestry Bureau has grown

E. camaldulensis, *E. pellita* and *C. citriodora* to large stem diameters and sold the timber for shipbuilding, furniture and flooring (Mo 2003). Recently, there has been greater interest in use of solid eucalypt timber for furniture and higher-value products. This requires logs of larger diameter than for pulpwood, and species with wood properties that are different from those that are optimal for pulp.

CERC has two key national projects, 'The cultivation of large diameter eucalypts' and 'Introduction of high-value eucalypt species'. These projects are testing more than 10 eucalypt species in provenance/family trials in the main eucalypt-growing provinces, researching silvicultural management regimes to grow large-diameter trees, and assessing wood properties (Yang 2003). Silvicultural research needs to focus on optimising planting density for yield and control of branch size, pruning to produce knot- and decay-free wood, and early thinning to enable retained trees to grow more rapidly to sawlog size. The ACIAR project on cold-tolerant eucalypts has contributed to this research through its support of thinning intensity trials of *E. globulus*, *E. maidenii* and *E. nitens* plantations in Yunnan and Australia (Zhang et al. 2003b).

High growth stresses and internal and surface checking during drying are features that can present severe problems in the recovery of high-value sawn eucalypt timber. There is increasing research in other countries on these problems, and studies have started in China. CAF's Research Institute of Wood Industry (CRIWI) and CERC are implementing a project funded by the International Tropical Timber Organization, 'Improved and diversified use of tropical plantation timbers in China to supplement diminishing supplies from natural forests', which aims to improve silvicultural practices for, and processing of, eucalypts for higher-value solid-wood products (Yang 2003). Results from research on processing eucalypts for solid-wood products in this and other projects were reported in the proceedings of the ACIAR international conference on 'Eucalypts in Asia' (see, for example, Du et al. (2003) and Jiang et al. (2003a,b)) and the IUFRO/ITTO 'International conference on plantation *Eucalyptus*—challenge in product development' (CRIWI 2005).

The China Eucalypt Research Centre started a 4-year research project 'Improving the value chain for plantation-grown eucalypt sawn wood in China, Vietnam and Australia: sawing and drying' in 2005, in cooperation with CSIRO Forestry and Forest Products and supported by ACIAR. The aim of this research is to improve sawing and recovery strategies to reduce timber degradation due to the distortion and splitting in logs when growth stresses are released in sawing operations. In 2006, five scientists from China and Vietnam attended the Timber Training Centre in Creswick, Australia, to train or upgrade skills in eucalypt timber sawing and wood drying, and were introduced to processing-research procedures (ACIAR 2006).

Sustainable management of eucalypt plantations in China

Eucalypts are now a significant part of the rural landscape in southern China. They are having environmental, social and economic impacts, and these may be positive or negative depending on how the plantations are managed. In planning sustainable management of eucalypt plantations in China and elsewhere, managers need to recognise that they are dealing with the attributes of particular species in the context of a particular technology for users in a socioeconomic setting (Raintree 1991).

There are general or broad-sense issues of whether using land and investing resources in eucalypt growing are environmentally, economically and socially sustainable. There is also a narrower-sense sustainability question of whether the eucalypts can be grown successively over many rotations without a decline in site productivity. These sustainability issues are being considered in China, and strategies for sustainable management of eucalypt plantations have been developed by, for example, Sino-Forest Corporation (Wei 2003), Stora Enso (UNDP 2006) and CERC (Xie 2003). However, local communities frequently lack reliable information about the social and environment impacts of plantation development, as was highlighted in Guangxi where a survey found people were seriously concerned about negative environmental impacts of eucalypt on humans, animals, crops, soil and water (UNDP 2006).

In some countries, planting eucalypts has resulted in considerable controversy and, in extreme cases, restrictions or bans have been placed on their use. The main concerns have been environmental impacts of large plantations, especially excessive water use, soil nutrient depletion and lack of biological diversity. There have also been social concerns, including that planting

eucalypts on potentially good agricultural land results in reduced food production and rural employment, diversion of forest products from local markets to larger industrial users, and the transfer of public or common land to private corporations.

The ecological effects of eucalypts have been reviewed many times over the past 20 years (see, for example, Poore and Fries (1985) and Davidson (1996)). Generally, the conclusions agree with those of Davidson (1996):

- Fast growth and high biomass production of eucalypts require the consumption of much water, and this consumption, though efficient in terms of biomass produced and one-half to one-third of that used by many agricultural crops, must be balanced with other requirements of finite water supplies, such as for agriculture, livestock and human consumption.
- Although the trees take up much less nutrients than most agricultural crops, the soil nutrient reserve of a site is finite and there is a nutrient cost for high biomass production of the trees vis-a-vis agriculture.
- Eucalypts, like many other trees, may not, by themselves, fully protect the soil from erosion.
- Eucalypts may not provide ideal habitats for the native wildlife and they may upset local traditions and values if projects are not carefully planned.
- Generally, eucalypts cannot be singled out as being always bad or as being uniquely different from other kinds of fast-growing trees under the same management conditions.

- Planted eucalypts will be successful only if they can grow well in the local conditions of climate and soil and only if they can provide the benefits required, either for industry or rural people, in a sound land-use and environmental management program. The tree planting must be accepted by, and benefit, the people directly and indirectly affected.

Criticism of the ecological effects of eucalypts has often masked concerns about social aspects of eucalypt plantations. In the report of a study of two social forestry projects in India and Thailand, Casson (1997) notes:

The failure of eucalypts to meet the social objectives of social forestry policies were[sic] found to outweigh any of the technical and ecological criticisms against the tree and *Eucalyptus* became a symbol and rallying point of grass roots resistance to government meddling, poor project planning and management.

A review of the ecological, economic and social effects of eucalypt planting concluded that allegations of adverse social effects were exaggerated and that possible social gains often outweigh these concerns (Sunder 1996). Such concerns may be due to a failure to provide appropriate information to those people potentially affected (UNDP 2006).

If eucalypt plantations are to be managed sustainably in China, managers must seriously consider the effects their activities will have on the environment and on the communities that are affected either directly or indirectly.

Environmental impacts

Biodiversity

Eucalypt plantations in southern China do not have the rich biodiversity of natural forests but, because most plantations have been established on degraded or deforested land, or have replaced slow-growing pine plantations or uneconomic horticultural crops, they pose little added threat to local biodiversity. A review of the Stora Enso plantation project in Guangxi concluded that it will cause no obvious landscape and biodiversity changes (UNDP 2006). However, it was recognised that Guangxi is highly diverse and contributes significantly to China's overall biodiversity. This biodiversity has

been threatened by degradation and fragmentation of habitats by land clearing and other human activities, so many species are threatened with extinction. The needs of these species and their habitats should be considered, particularly if plantation sites are close to key natural habitats, such as existing or proposed nature reserves. Similar concerns exist to a greater or lesser extent in other provinces.

Water

Potentially excessive water use by eucalypt plantations that may deplete groundwater resources and adversely affect farmers irrigating their crops in the dry season has been an issue in some countries and of concern in China. In 1996, ACIAR funded a project that modelled water use and the growth of eucalypts under different management practices on Leizhou Peninsula, Guangdong. In this area, mean annual rainfall varies between 1,300 and 1,800 mm. The research concluded that the *E. urophylla* plantations were not using excessive amounts of water compared with agricultural crops, and that water use of the eucalypts did not appear to be harming the water supply in this area (Lane et al. 2003; van Bueren 2004).

Consideration of the water-use issue in Guangxi concluded that water use of eucalypts will not be a constraint in areas of high rainfall and high humidity. However, there was little information available on water balance at sites with less than 1,200 mm/year rainfall, such as Dongmen and, as a precaution, plantation managers should consider introducing wider spacing of plantations to reduce water use per unit area (UNDP 2006). The UNDP review also identified a knowledge gap on the effects on the quality of run-off water of heavy fertiliser applications in intensively managed eucalypt plantations, and recommended monitoring these effects.

Nutrient depletion

Many of the soils used for eucalypt plantations in southern China have an inherently low nutrient status, and plantations typically have rapid early growth, followed by a decline in leaf area and growth rate. This appears to be nutritionally induced by the loss from the soil, by physical and biological processes, of nitrogen and other essential nutrients within 2–3 years (Morris 2003).

Very intensive mechanical site preparation has a number of negative environmental effects, including accelerated soil nutrient loss. Major nutrient losses can occur during harvesting, when stumps, existing ground vegetation and litter are removed, and from accelerated erosion if the soil is prepared to a fine tilth. Slash retention after harvesting may improve the status of soil organic matter in second-rotation crops but, if the slash is removed, nitrogen fertilisation may be required (Xu et al. 2004). Minimal site disturbance and retention of slash can reduce nutrient depletion. In Guangxi, management practices in Stora Enso's eucalypt plantations will aim to enhance the chemical and physical properties of soils to achieve sustained productivity. The company will use tractor ripping for site preparation on flat lands, prepare planting pits on hilly lands, and minimise site disturbance and removal of organic matter (UNDP 2006).

A number of studies have correlated eucalypt growth, nutrition and soil nutrient availability in China. For example, an ACIAR project concluded that, in the cooler areas, there are relatively widespread deficiencies of N, P, K, B and Cu, and that fertiliser application is necessary to achieve economically successful establishment (Baker et al. 2003) (see 'Nutrient management' section). Nutrient management in eucalypt plantations has been reviewed by Xu and Dell (2003) and, although inorganic fertilisers are now commonly used in commercial eucalypt plantations in southern China, the rates of P application are low and knowledge of the effect of P application on nutrient utilisation by eucalypt plantations is limited (Xu et al. 2002). The high cost of fertilisers, estimated at 35–40% of establishment and management cost (Barr and Cossalter 2004), may be a deterrent to their application at optimal levels. Addition of inorganic fertilisers to replace nutrient losses is one remedy, but fertiliser efficiency can be reduced by volatilisation, fixation, leaching etc. and it is desirable to complement fertiliser use by appropriate management practices, such as residue retention, to minimise losses of nutrients from the site (Xiang and Simpson 2006).

Recognition of the fragility of the soils and the potential for nutrient depletion has led to considerable research to determine silvicultural practices that will minimise any negative effects. The sustainability of eucalypt plantations will be greatly enhanced if conservative practices are applied generally in southern China.

Pests and diseases

When eucalypts were first grown outside Australia in the absence of coevolved parasites, they grew very healthily. More recently, they have suffered damage, especially from leaf diseases in the tropics and subtropics. Pathogens may be introduced from Australia or spread from local plants to the introduced trees. Foliar and stem diseases have damaged some eucalypt plantations elsewhere in Asia. Leaf- and shoot-blight pathogens have caused defoliation and shoot death, and have the potential to reduce growth rates and product quality. These diseases are favoured by warm, humid climatic conditions, similar to those in some of the southern provinces of China, where they are a potential threat. The bacterial wilt, *Ralstonia solanacearum*, is already present in Chinese eucalypt plantations and damages or kills young trees. A manual of diseases of eucalypts in South-East Asia provides information on the status of potential pathogens and how to manage them (Old et al. 2003), and much of this information is relevant to China.

Termites are currently the most damaging pests of eucalypts in southern China, but there are also periodic attacks by defoliators, wood-borers and bark-feeders. The cost of lost production due to insect pests in 2001 was estimated at US\$4.1 million, and this is expected to rise significantly as the plantation area expands (Pang 2003).

There is a national responsibility to enforce international quarantine regulations to minimise the risk of importing serious pests and diseases, such as the eucalypt rust, *Puccinia psidii*. At the local level, integrated pest management should be practised to reduce the economic loss caused by pests to acceptable levels with minimal environmental side effects. Initially, this involves minimising the problem by careful site selection and species–site matching of resistant species/clones, followed by sound silvicultural practices and monitoring of plantations for the incidence of pests and diseases (Gadgil et al. 2000).

Eucalypt plantations in southern China currently rely on planting material from a very narrow genetic base, presenting a serious risk to productivity and sustainability through infestation by pests or diseases. Despite substantial investments in tree breeding, the number of clones being deployed in commercial eucalypt plantations is very small: an estimated 90% of plantations

established in recent years use only three clones (Barr and Cossalter 2004). So narrow a genetic base is contrary to good plantation management practice and is below the threshold of diversity for an acceptable level of risk for damage by pests and diseases (Evans and Turnbull 2004).

In Brazil, it is claimed that landscape diversity may help reduce risks from pests and diseases to eucalypt plantations (Campinhos 1999). In many areas of southern China, there is a mosaic of agricultural ecosystems and native and planted forests coexisting in the landscape, and management at a landscape level should be a major consideration for the long-term sustainability of eucalypt plantations (UNDP 2006). Genetic diversity is critical for the long-term sustainability of plantation estates, and it is essential that an adequate number of productive clones with enduring field resistance to major diseases be developed and appropriately deployed in Chinese plantations.

Socioeconomic impacts

China's demand for pulpwood fibre, and the development of eucalypt plantations to provide it, will affect rural communities and pose both threats and opportunities (He and Barr 2004). Productive eucalypt plantations and associated industries can result in greater employment and have wider benefits to local and regional economic development, public infrastructure construction and maintenance, and in domestic energy supplies (Zhou et al. 2002). Eucalypts are providing farmers with an alternative source of income and can be expected to make a positive contribution to rural incomes, and hence to local living standards. Farmers will gain income by selling wood from their own land, renting out their land or obtaining off-farm employment with plantation companies or in wood-processing industries. Conversely, the development of the eucalypt-based MDF and pulp and paper industries in some areas will have negative effects on other areas where uncompetitive factories will close and farmers who supply raw materials, such as rice straw, to these industries will lose their markets.

Plantation ownership

Smallholder farmers have the potential to earn significant income by growing eucalypts and selling the wood, either on the open market, or through outgrower schemes linked to particular pulp companies or other wood processors. Several factors will influence the extent to which farmers can derive income from growing eucalypts, including (Van Bueren 2004):

- access to forest lands and security of tenure
- access to capital and timber markets
- quality of roads and infrastructure for transporting wood
- management skills and ability to grow productive plantations
- access to technical advice and good-quality planting stock.

Opportunities to derive income from eucalypt growing are greater for the middle- and higher-income groups, as they generally have better education and management skills, and greater access to capital. In Guangxi, it is the higher-income households that are interested in taking loans for plantation development, whereas poorer households will mostly be involved as seasonal workers and/or through receiving payments for land where the plantation takes place (World Bank 2005).

Higher-income households in more developed areas may prefer to have loans to grow their own trees for sale but, in remote upland areas, there is preference for a joint operation with a company or forest farm. There are numerous variations of contractual arrangements between growers and companies, involving greater or lesser inputs from the households. The social assessment for the GIFDCP surveyed households and identified the following perceived benefits from contractual production arrangements (World Bank 2005):

- The household 'buys a share' in the plantation with land instead of capital and does not bear any risk related to the loan.
- The company or forest farm is responsible for the plantation capital and technology.

- The arrangement allows intensive operations to produce high-quality plantations with high economic benefit.
- Farmers can keep working in their own fields during the peak of the farming season.
- Villagers who work off-farm outside the village all year round may be attracted to return home to participate in plantation activities.
- Related development promoted by the planting will create many job opportunities in transportation, marketing etc.
- The plantation will create a good environment for the community.

Village collectives in parts of southern China retain substantial areas of forest land and have established and manage significant areas of eucalypt plantations. Recent tenure reforms have resulted in more forest being owned and managed by individual households. Collectives and households are actively involved in commercial forestry contracts with wood-using enterprises and there is concern about how to ensure that contracts are fair and transparent when vulnerable groups enter production contracts with large enterprises. Limited access to information among communities and households, and their low capacity for negotiation with enterprises, might lead to production arrangements with these enterprises that may not be fully appropriate or fair. Lack of transparency in contracts with enterprises, and in plantation accounting, might lead to unclear or unfair benefit sharing for communities or households (World Bank 2005). On the positive side, revenue from plantations owned by collectives may be used directly, or may be taxed by village committees, to upgrade or build village infrastructure such as schools, irrigation and reticulated water systems, roads and power facilities (Zhou et al. 2002, in van Bueren 2004; World Bank 2005).

Land rental

Since the late 1990s, long-term land leasing from households has become the most common practice of companies investing in plantation development. Although the phrase 'company + household' is generally used to designate contractual arrangements, it usually refers to either an individual household or village collective. In Guangxi, for example, extensive

plantation development in the past 10 years has occurred on collective lands in hilly regions previously considered 'wastelands'.

Various land types are used for eucalypt plantations, most with relatively low rental values, as the more fertile land is used for more profitable agricultural crops. Those renting land for plantations pay annual rents of up to 1800 yuan/ha for flat land in Guangdong and Guangxi, but only about 100 yuan/ha for hilly or mountainous land (van Bueren 2004). Surveys by UNDP (2006) found that where land is 'owned' by individual farmers they appear to make a rational choice to rent out their land for tree planting, despite the possibly lower income per unit area relative to other options, because of constraints such as the financial strength, technical knowledge and economies of scale needed to develop the alternatives. Poorer households may be more willing to rent their land because they lack financial resources to invest in it, have insufficient household labour to work it, have other capital requirements, or wish to use the rental money as core investment to escape from poverty. Chinese farmers are often not comfortable with long-term contracts (Endo 2003) and companies face a major challenge to communicate and negotiate with the very many households involved in land rental for plantation forestry.

Decisions over whether or not to rent collective land may be more contentious, as the decision-making process often involves relatively few members of the community, and there may be diverse views about how the income will be spent and/or whether the rent offered is reasonable. Dissatisfaction with the decision-making process may adversely affect the attitudes of the community to eucalypt plantations. While such conflicts are best resolved at the local village level, plantation companies may be able to assist the process with support and encouragement, given their interest in having harmonious land leasing (UNDP 2006).

A large proportion of rural households in the hilly areas lives in poverty and benefits from renting land for plantations (Cossalter and Barr 2005). While land rental may have positive benefits for the rural poor, there is concern that inequitable and/or inflexible lease contracts or share agreements may result in tensions between plantation companies and collective landowners. Some plantation companies have sought to lock in a low rental fee for the duration of long-term contracts. In Guangxi, Cossalter and Barr (2005) found

that only 40% of contracts have a clause in the lease revising the rental price in the first 3–10 years, and say that experience in other countries has shown that company–community agreements frequently fail where the contract is perceived to be inequitable by one or both parties. The social assessment of the GIFDCP had similar concerns, especially where very poor ethnic communities were involved, and recommended that, in contrast to current practice in Guangxi, no plantations under the project take place under a land-lease arrangement whereby land-use rights could be legally fully transferred to a commercial operator in the long term. It was suggested that the duration of land-lease arrangements should be significantly shorter than current practice (World Bank 2005).

Off-farm employment

Private companies developing large areas of eucalypt plantations require unskilled labour for establishment, maintenance and harvesting. Local villagers and people migrating from poorer provinces, such as Guizhou, Hunan and Sichuan, will meet some of the labour requirements. Employment in the pulp mills and wood-processing factories is likely to benefit urban dwellers as much as rural communities.

A study in Guangxi found that tree-plantation development, particularly in hilly areas, offered valuable opportunities for rural employment and household income generation (Cossalter and Barr 2005). Development of plantations in hilly areas is labour-intensive, although the work is largely seasonal and unskilled. There are often no alternative development options for the land being used for tree planting, and few other job opportunities. Economic decline has been common in recent years many hilly areas of Guangxi, and a large part of the younger rural population has been forced to work outside the region. Plantation development on flat lands in the coastal region of Guangxi generally provides more profitable sites for wood production, but many of these areas have highly mechanised operations and so provide relatively fewer employment opportunities

A social assessment of the GIFDCP project in Guangxi found that there has been a strong movement of poor farmers to take up off-farm work opportunities after migration was permitted in the mid-1990s (World Bank 2005). The planting of eucalypts has increased the need

for non-local seasonal workers in Guangxi, with most of these workers coming from very poor areas within the region and poor areas in neighbouring provinces, especially Guizhou. Forestry provides opportunities to farmers with limited skills, and is less dangerous than mining. The living conditions of farmers taking up these opportunities can be harsh, as they typically live in tents and may not have access to clean water, although lack of access to safe water is also widespread among local residents in poor areas (World Bank 2005).

It is estimated there will be between 12,400 and 14,400 full-time employees in the Stora Enso plantation project in Guangxi when it is fully operational. An estimate of direct and indirect employment for plantations and the planned pulp mill is 30,000–35,000 full-time positions (UNDP 2006). Nevertheless, an audit of plantation forestry in the tropics (Cossalter and Pye-Smith 2003) suggests that plantations often bring fewer benefits in terms of employment than is claimed by companies within the industry. This may be the case in China because, while development of wood-based kraft pulp production will provide employment opportunities for both rural and urban dwellers in some provinces, shrinkage of the non-wood pulp industry will diminish employment in other areas. In the past, non-wood raw materials, such as straw and other agricultural residues, made up about 70% of fibre used to produce pulp in thousands of small- and medium-size factories widely distributed throughout the country. Although inefficient and polluting, these enterprises provided employment for large numbers of people and a source of income for farmers supplying agricultural residues. It has been estimated that non-wood pulp production will decline by 1.5–3.5 million tonnes by 2010 and that 700 or more factories will close, in addition to the many that have already done so (He and Barr 2004).

An estimated 10,000–15,000 ha of Guangxi's pine and Chinese fir plantations are converted into eucalypt plantations each year. Pine and Chinese fir plantations provide thinning products and harvest residues that are sold at low prices to a large number of mills producing cheap reconstituted panels for the domestic market. Short-rotation eucalypt plantations do not provide thinning products, and the loss of pine and Chinese fir plantations may threaten the economic viability of small- to medium-scale panel mills as they lose access to cheap raw material (Cossalter and Barr 2005). This could also reduce local employment opportunities.

Fuelwood

It has been the right of communities to have unrestricted access to harvest litter in Chinese forests and plantations. Before the 1980s, almost all harvest residues, understorey plants and litterfall on the soil surface in eucalypt plantations in southern China were collected for fuel and/or to produce ash for fertilising agricultural crops (Figure 12). The rural poor continue this practice. On Leizhou Peninsula, Guangdong, 70% of poor households depend totally on litter from plantations for fuel (Zhou et al. 2002, in van Bueren 2004) and, in Guangxi, the poorest households in the community also rely on fuelwood from collective and private-use forest land (UNDP 2006). While most litter collection is for domestic fuel, some farmers and contractors sell litter to fuel brick and lime kilns (van Bueren 2004).

The harvesting of forest floor litter, including twigs, leaves, fallen branches and harvesting residues, is of great concern for plantation managers, as the removal has the potential to reduce site fertility, especially soil organic carbon and nitrogen stores. Research has confirmed that organic residue retention in plantations has a positive effect on tree growth, especially on soils with low nutrient reserves, and is a practice that should be encouraged to ensure plantation sustainability (Tiarks et al. 2004). There appear to be substantial economic benefits in retaining organic residues on site (Zhou and Loane 2003).

Banning litter collection and removal of harvesting residues will disadvantage harvesting contractors and low-income groups, who would lose income or a free resource. This is likely to have a negative impact on welfare and social sustainability. This conflict between good forestry management practice and the social issue of fuelwood gathering needs to be resolved. Zhou and Loane (2003) suggest either compensating these groups or continuing to allow fuelwood collection while increasing inputs of inorganic or organic fertilisers. Harvesting contractors could be compensated by increased payments and villagers could be allowed to cull weak trees for fuel.

In Guangxi, Stora Enso managers have indicated that, while the company wants to retain leaf and bark residues on site for soil protection, nutrient recycling and water conservation, they will permit collection of fallen woody branches and woody harvesting residues for fuelwood (UNDP 2006), and some plantation managers elsewhere also tolerate fuelwood collection.



Figure 12. Litter raked for fuel in a Guangxi eucalypt plantation [J. Turnbull]

Concluding remarks

While it is more than a hundred years since eucalypts were introduced into China, it is only in the past 25 years, in line with changes in government policy to encourage plantation development, that domestication of eucalypts has proceeded rapidly. Research by Chinese institutions, often supported by international development assistance agencies, has achieved substantial increases in plantation productivity. The AusAID-funded project at Dongmen in the 1980s provided an excellent early start, and the longer-term support of cooperative research by ACIAR, together with ongoing, informal collaboration, has been crucial in providing a basis for developing sustainable practices and extending eucalypt plantations throughout southern China. China now supports one of the largest areas of eucalypt plantations in the world, and these will increasingly make a significant contribution to its forest resources and to the country's economy.

Tree breeding and management practices have doubled the average productivity of eucalypt plantations in many areas. The high productivity currently being achieved in the third and fourth rotations of intensively managed eucalypt plantations at Dongmen is evidence of the success of domestication and high standards of management. Retention of litter and logging residues on site, careful site preparation and control of soil erosion, and judicious use of fertiliser are key silvicultural practices. These practices, and the availability and use of improved genetic planting materials, have contributed to enhanced productivity and profitability and sustainable soil management of eucalypt plantations at Dongmen and elsewhere. However, failure to fully implement optimal silvicultural practices in many plantations is an ongoing problem that will reduce some of the benefits of population improvement.

Full potential productivity gain from continuing genetic improvement may not be reflected in actual increases in total production because of the, almost inevitable, continuing and progressively adverse effect of pests and diseases, and the effect of repeated cropping on site resources. Continuing population improvement is one of the best tools available for offsetting this attrition and to sustain high levels of production. Although substantial productivity gains have been achieved, there is potential for further gains. This is clearly demonstrated in other crop plants where current yields are many times those of the wild populations. Annual yields of rubber (*Hevea brasiliensis*), for example, have increased from 400 kg/ha to over 2,000 kg/ha (Bonner 1991).

It is critical that the cost of producing wood and woodchips in China be competitive with comparable imports if the plantations are to remain profitable. Efforts are being made to further enhance the yield and quality of products of new and existing plantings via focused R&D and these need to be encouraged. It is essential that government and industry continue to provide sufficient support for ongoing R&D and that there be a high level of effective cooperation and communication between individuals, companies and government agencies.

There are questions about the sustainability of fast-growing, short-rotation, eucalypt plantations. At the landscape level, there is little evidence that the plantations will have significant negative effects on biodiversity. Similarly, water use by eucalypt plantations does not appear to harm local water supplies in areas where rainfall and atmospheric humidity is relatively high. In drier areas (less than 1,200 mm/year rainfall), however, impacts on water supplies should be monitored and, if necessary, silvicultural practices, such as tree spacing and thinning, modified to reduce water

use. Nutrient depletion and/or erosion of the relatively fragile soils in much of southern China are of concern, but can be managed if appropriate silvicultural practices, such as minimal cultivation, organic matter retention and fertilisation, are consistently applied. A greater risk to sustainability is the potential for serious damage by pests and diseases to monoclonal plantations lacking genetic diversity.

The eucalypt plantations grow rapidly and produce wood fibre that has the potential to support a major pulp and paper industry and other wood-based industries such as MDF, sawn timber and veneer. However, the availability of suitable land, and competition with agricultural crops for higher-quality land, are obstacles to companies developing an adequate plantation base. Consequently, companies managing integrated forest–pulp–paper industries will probably remain at least partially reliant on imported woodchips for several years to come.

Government policies will have a major influence on how plantations develop, to what extent they are profitable to growers, and whether sufficient wood can be produced economically to meet the requirements of the wood-based industries. The national government has already supported the establishment of industries based on eucalypt plantations through a variety of financial and tax incentives designed to encourage foreign investment in the wood fibre, pulp, paper, and wood-processing sectors. There has been a series of policy initiatives to encourage plantation development and wood marketing but more needs to be done. Reforms that establish ownership of the previously collective-owned forests, and allocation of individual property rights, are a recent positive development and need to be complemented by implementation of government promises to reduce high fees and taxes, and standardise transfer of property rights to ensure that farmers have clear legal rights to their land and forests. Harvesting quotas and associated logging permits remain a disincentive to private growers who would benefit from a less restrictive and bureaucratic system.

Eucalypts are providing new sources of income for individual farmers and collectives that have the necessary management skills, access to capital and land to grow plantations. Employment opportunities being created in some areas will help some of the poorest local households, or poor migrants from other provinces, to secure off-farm income. Many rural households in hilly or mountainous areas live in poverty and are benefiting from renting land for plantations. Local infrastructure and facilities may benefit from local taxes on eucalypt wood sales or direct company support. These are very positive outcomes, but there are concerns that long-term contracts for use-rights on land, or production contracts, may lack transparency and disadvantage households with insufficient information and poor negotiation skills. In time, this could lead to conflict, and it is in the long-term interest of companies to negotiate fair and transparent contracts. There is also need for good communication by companies and government agencies to all levels of stakeholders relating to contractual arrangements and resolution of the problem of access to fuelwood in plantations.

Overall, it appears that the socioeconomic impacts of eucalypt plantations are positive, but although plantation development has contributed significantly to poverty alleviation in some areas, it is probable that greater benefits accrue to higher-income groups.

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IMPACT ASSESSMENT SERIES

No.	Author(s) and year of publication	Title	ACIAR project numbers
1	Centre for International Economics (1998)	Control of Newcastle disease in village chickens	8334, 8717 and 93/222
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4	Watson, A.S. (1998)	Raw wool production and marketing in China	8811
5	Collins, D.J. and Collins, B.A. (1998)	Fruit fly in Malaysia and Thailand 1985–1993	8343 and 8919
6	Ryan, J.G. (1998)	Pigeon pea improvement	8201 and 8567
7	Centre for International Economics (1998)	Reducing fish losses due to epizootic ulcerative syndrome—an ex ante evaluation	9130
8	McKenney, D.W. (1998)	Australian tree species selection in China	8457 and 8848
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10	AACM International (1998)	Conservation tillage and controlled traffic	9209
11	Chudleigh, P. (1998)	Post-harvest R&D concerning tropical fruits	8356 and 8844
12	Waterhouse, D., Dillon, B. and Vincent, D. (1999)	Biological control of the banana skipper in Papua New Guinea	8802-C
13	Chudleigh, P. (1999)	Breeding and quality analysis of rapeseed	CS1/1984/069 and CS1/1988/039
14	McLeod, R., Isvilanonda, S. and Wattanutchariya, S. (1999)	Improved drying of high moisture grains	PHT/1983/008, PHT/1986/008 and PHT/1990/008
15	Chudleigh, P. (1999)	Use and management of grain protectants in China and Australia	PHT/1990/035
16	McLeod, R. (2001)	Control of footrot in small ruminants of Nepal	AS2/1991/017 and AS2/1996/021
17	Tisdell, C. and Wilson, C. (2001)	Breeding and feeding pigs in Australia and Vietnam AS2/1994/023	
18	Vincent, D. and Quirke, D. (2002)	Controlling <i>Phalaris minor</i> in the Indian rice–wheat belt	CS1/1996/013
19	Pearce, D. (2002)	Measuring the poverty impact of ACIAR projects—a broad framework	
20	Warner, R. and Bauer, M. (2002)	<i>Mama Lus Frut</i> scheme: an assessment of poverty reduction	ASEM/1999/084
21	McLeod, R. (2003)	Improved methods in diagnosis, epidemiology, and information management of foot-and-mouth disease in Southeast Asia	AS1/1983/067, AS1/1988/035, AS1/1992/004 and AS1/1994/038
22	Bauer, M., Pearce, D. and Vincent, D. (2003)	Saving a staple crop: impact of biological control of the banana skipper on poverty reduction in Papua New Guinea	CS2/1988/002-C
23	McLeod, R. (2003)	Improved methods for the diagnosis and control of bluetongue in small ruminants in Asia and the epidemiology and control of bovine ephemeral fever in China	AS1/1984/055, AS2/1990/011 and AS2/1993/001

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No.	Author(s) and year of publication	Title	ACIAR project numbers
24	Palis, F.G., Sumalde, Z.M. and Hossain, M. (2004)	Assessment of the rodent control projects in Vietnam funded by ACIAR and AUSAID: adoption and impact	AS1/1998/036
25	Brennan, J.P. and Quade, K.J. (2004)	Genetics of and breeding for rust resistance in wheat in India and Pakistan	CS1/1983/037 and CS1/1988/014
26	Mullen, J.D. (2004)	Impact assessment of ACIAR-funded projects on grain-market reform in China	ANRE1/1992/028 and ADP/1997/021
27	van Bueren, M. (2004)	Acacia hybrids in Vietnam	FST/1986/030
28	Harris, D. (2004)	Water and nitrogen management in wheat–maize production on the North China Plain	LWR1/1996/164
29	Lindner, R. (2004)	Impact assessment of research on the biology and management of coconut crabs on Vanuatu	FIS/1983/081
30	van Bueren, M. (2004)	Eucalypt tree improvement in China	FST/1990/044, FST/1994/025, FST/1984/057, FST/1988/048, FST/1987/036, FST/1996/125 and FST/1997/077
31	Pearce, D. (2005)	Review of ACIAR's research on agricultural policy	
32	Tingsong Jiang and Pearce, D. (2005)	Shelf-life extension of leafy vegetables—evaluating the impacts	PHT/1994/016
33	Vere, D. (2005)	Research into conservation tillage for dryland cropping in Australia and China	LWR2/1992/009, LWR2/1996/143
34	Pearce, D. (2005)	Identifying the sex pheromone of the sugarcane borer moth	CS2/1991/680
35	Raitzer, D.A. and Lindner, R. (2005)	Review of the returns to ACIAR's bilateral R&D investments	
36	Lindner, R. (2005)	Impacts of mud crab hatchery technology in Vietnam	FIS/1992/017 and FIS/1999/076
37	McLeod, R. (2005)	Management of fruit flies in the Pacific	CS2/1989/020, CS2/1994/003, CS2/1994/115 and CS2/1996/225
38	ACIAR (2006)	Future directions for ACIAR's animal health research	
39	Pearce, D., Monck, M., Chadwick, K. and Corbishley, J. (2006)	Benefits to Australia from ACIAR-funded research	
40	Corbishley, J. and Pearce, D. (2006)	Zero tillage for weed control in India: the contribution to poverty alleviation	CS1/1996/013
41	ACIAR (2006)	ACIAR and public funding of R&D, Submission to Productivity Commission study on public support for science and innovation	
42	Pearce, D. and Monck, M. (2006)	Benefits to Australia of selected CABI products	
43	Harris, D.N. (2006)	Water management in public irrigation schemes in Vietnam	LWR2/1994/004 and LWR1/1998/034
44	Gordon, J. and Chadwick, K. (2007)	Impact assessment of capacity building and training: assessment framework and two case studies	
45	Turnbull, J.W. (2007)	Development of sustainable forestry plantations in China: a review	