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EUCALYPT ALTERNATIVES TO *ACACIA MANGIUM* IN WET TROPICS

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Acacia mangium was planted on a large scale in the 1990s as it was thought to be the solution for afforestation in Sarawak. However, the trees are now being decimated by fungal diseases which attack its stem and its roots. The genetic variability of the species is limited and thus, there is little hope of saving the species through selection for resistance or tolerance. Hybridisation with *A. auriculiformis* holds some promise though, as witnessed in Vietnam. Selected hybrids show resistance to some of the diseases, grow well and can easily be propagated by vegetative means. The switch to *A. crassicarpa* presently holds much promise for poor and peat soils and some disease resistance, and there may be a few different acacia species still available for testing. Nevertheless, controlled hybridisation of the acacias is not easily accomplished. Except for the hybrid mentioned above, vegetative propagation is not easy, such as is with the eucalypts. The eucalypts (*E. pellita, E. deglupta, E. brassiana, E. tereticornis* var. *tereticornis*, possibly also *E. leptophleba,* especially Papua Island and northern Australian provenances) are a good starting point for eucalyptus cultivation in equatorial climates like Sarawak, along with the use of hybridisation and vegetative propagation. These species can form the pillar for selection, formation of landraces, hybridisation and vegetative propagation for the humid and hot equatorial climate. Eucalypts are more demanding on soil quality, but easy to hybridise and amenable to vegetative propagation and with a wide array of wood qualities. Their gene pools and the clones obtained can be widened with genetic inputs of a variety of other species being bred into eucalypts in sub-tropical regions where they are extremely successful. A wide genetic base and quick replacement for more productive and resistant clones form one of the bases for successful short-rotation forestry. About 25 additional species are suitable for hybridisation. Possibilities within the genus *Corymbia* are briefly discussed in this paper.

Keywords: Afforestation, Acacias, hybrids, vegetative propagation, *Eucalyptus, Corymbia*

INTRODUCTION

In the 90s, *Acacia mangium* was planted on a large scale in Sarawak as it was deemed as the best choice and a viable alternative for Sarawak's hot and humid climate. Harwood (1998) reported that *A. crassicarpa* and *A. mangium* were promising species along with the hybrid *A.* × *mangiiformis* (*A. mangium* × *A. auriculiformis*) (Maslin et al. 2019) and *Paraserianthes falcataria* (now known as *Falcataria moluccana)*. These species have been planted in Southeast Asia, particularly in Indonesia, Malaysia, and Vietnam as they have been proven to be resilient and pest resistant. Eucalypts did not appear promising at that time. Koutika and Richardson (2019) found *A. mangium* to be useful in restoring biodiversity but a challenge is that the species is invasive in many environments.

According to Harwood (1998), acid and infertile (usually leached, low base saturation, often low aeration) soils of Sarawak were not favourable to most plantation trees. The high year-round humidity and high rainfall were particularly conducive to diseases like leaf-blights for the sub-tropical eucalypts which were very successful elsewhere in sub-tropical environments. He warned in 1998 that for *Acacia mangium* "*Significant disease problems are anticipated.*"

This ominous prediction turned out to be a tragic reality. Tarigan et al. (2011) described *Ceratocystis mangenicans* as a wilt disease that now continues to ravage plantations everywhere in SEA. The conidia of the fungus remain in the soil for a very long time (Nasution et al. 2018) and it is believed to be spread mainly via insects after the wounding of the tree by pruning or by animals. Spreading through air is a distinct possibility. *Ganoderma philippii* is another type of fungal disease which targets *A. mangium* (Page et al. 2020) through the root system. Heart rot diseases are already widespread in *Acacia mangium.* Lee (2018) emphasised the need to breed for disease resistance and search for other means (hybridisation, cloning for example) to evade the threats of diseases.

One of the limitations of *Acacia mangium* is that it has a very low variability and few genes for resistance to *Ceratocystis acaciivora* (Brawner et al. 2015). This means that in the best of the cases, selection progress for resistance will be very slow through tree generations. An alternative is hybridisation with *A. auriculiformis*, which has some genes for resistance, and it additionally can be propagated by cuttings, as can also be done with their hybrids (Chi et al. 2019). Hybridisation and clonal propagation combined are powerful tools for quickly obtaining resistant clones and can be used to stay ahead of the advancement of diseases, while at the same time striving for adaptation and productivity (Assis 2006 & 2011, Gonçalves et al. 2001). There are more than 1,000 species of Acacia in Australia alone (Boland et al. 2006), but there are only a few of commercial growth potential, contrasting with the genus *Eucalyptus* with over 700 species, of which at least 25 species are grown in tropical and subtropical regions in the world, with wide possibilities of hybridisation and cloning.

In Vietnam, there have been large scale trials with the hybrid *Acacia mangiiformis* (*A. mangium* × *E. auriculiformis*) (Maslin et al. 2019). It takes years of screening to produce favourable characteristics and adaptation to different environments which has to be done in the spots where hybrids are to be planted. There are more Acacia species than the above to be screened for resistance and growth, but the adapted species with potential growth are limited in numbers. Hybridisation does not happen naturally between many Acacia species for genetic and geographic distances and flowering phenology. Even where possible, acacias are difficult to hybridise manually due to the small size and anatomy of its flowers. The method usually applied in hybridisation is by planting the two desired clones or species for hybridisation side by side and then screening for hybrids in the seedlings produced during the period of synchronous flowering.

The hybrid *A.* × *mangiiformis* is of commercial importance and capable of vegetative propagation, but no other hybrid in the acacias has yet been shown to be of plantation value. The genetic potential between only two species is limited to the combination of the variability exhibited by each of the species involved. Hybridisation possibilities are limiting factors in acacia hybridisation, and most of the acacias do not exhibit the very useful potential of cheap and easy vegetative propagation, as is the case with most of the eucalypts planted worldwide. The more expensive laboratory way of tissue culture is sometimes used. Vegetative propagation and the wide possibility of hybrid combinations added to the ease of hybridisation allow for quick development of new clones, testing and replacement of previous less productive ones for greater productivity and against new disease threats. The commercial hybrids of wide and different genetic origins produced constitute a genetic reservoir for a quick replacement of suddenly susceptible or less productive clones. This is what is being done worldwide in eucalypt hybridisation in subtropical climates and to a lesser degree within the genus *Corymbia*.

While *A. mangium* is still planted on a wide scale, alternative species have been sought. *A. crassicarpa* is currently thought to be less susceptible to *Ceratocystis* and *Ganoderma* while being more tolerant of poor soils. It may have a more genetic variability than *A. mangium,* but hybridisation possibilities with other species are limited. Another species proposed by Harwood in 1998 is *Falcataria moluccana* from the tropical rain forest in Papua and PNG. Its wood is of low density but it has several uses and is being planted on a commercial scale in many countries, in Sarawak and SEA. Unfortunately, it has proved to be very difficult to propagate by vegetative means (Harwood 1998) but some genetic improvement based on selection is taking place in Sarawak. It is therefore worthwhile to look into the eucalypts for solutions in the equatorial climate.

Eucalypts and climate

Eucalypts are divided into seven genera: *Eucalyptus*, *Corymbia*, *Angophora*, *Stockwellia*, *Allosyncarpia*, *Eucalyptopsis* and *Arillastrum* (Ladiges et al. 2003). Of these, species in the genera *Eucalyptus* and *Corymbia* are the main planted ones throughout the world.

Although the 700–800 *Eucalyptus* species are fewer than the approximately one thousand *Acacia* species in Australia alone, they include approximately 25 successful plantation forest species around the world, compared with the handful plantation tree species of *Acacia* with limited hybridisation possibilities (*A. mangium,* *A. crassicarpa, A. auriculiformis, A. aulacocarpa, A. midgleyi*, possibly also *A. peregrina* and the tetraploid *A. koa*) (Friday 2018). Currently, there are 8 sub-genera recognised within *Eucalyptus*, but the majority of plantation species belong to the sub-genus *Symphyomyrtus*, which comprises 450 species (Nicolle 2019) with wide possibilities of hybridisation among them (Potts et al. 2003) but these are not always easy to obtain. Similarly, within the genus *Corymbia*, consisting of 95 species in two sub-genera (Nicolle 2019) the chances for hybridisation and adaptation are also high (Dickinson et al. 2007). *Eucalyptus* and *Corymbia* hybrids when planted outside their native range very frequently display heterosis. This vigour is one of the reasons for the remarkable success of eucalypts worldwide.

Different *Eucalyptus* species are adapted to a wide array of natural environments, from cold winters in Tasmania northward into areas of very low rainfall, regular, summer or winter rainfall, up into the north, with some species trespassing Australia into the Sunda archipelago in Indonesia and into Papua and Papua New Guinea, and *Eucalyptus deglupta* even extending north of the equator on Sulawesi Island and reaching Mindanao in the Philippines (Davidson et al. 2018). A few species are exclusively extra-Australian (*E. deglupta, E. alba* var. *alba, E. orophila, E. urophylla, E. wetarensis*) (Nicolle 2019). Species native to Australia *and* extra-Australian are *E. leptophleba, E. brassiana, E. tereticornis* subsp. *tereticornis, E. pellita* from northern Queensland which also grows in Papua-Indonesia and Papua New Guinea (Nicolle, 2019). Hill and Johnson (2000) classified the portion of this species occurring north of 15°S in Queensland and on Papua as *E. biterranea*. This is not widely accepted. House and Bell (1996) using isozymes found no support for the separation of *E. pellita* from Papua New Guinea into a separate entity. The species from areas in PNG and Papua-Indonesia are of high interest for SEA because they have evolved in areas of much rainfall and high humidity, particularly *E. pellita*.

Extraordinary progress with eucalypt productivity has been achieved in many places in the world after vegetative propagation was developed in the 1970s and onwards. In Brazil, pure species with uncertain hybrids were planted until that time, with a productivity of maximum 15 m^3 ha^{-1} $year^{-1}$ at age 6–7 years and large individual variability (Assis 2006). After the cloning technique was well mastered and better clones were produced, from the 1980s onward productivity increased at a speed of 2.5% per annum (Gonçalves et al. 2013). Hybridisation followed quickly, and by 2005 a technique had been developed, which allowed mass-hybridisations to be performed in a quick and efficient manner, called "Artificially Induced Protogyny" –AIP- (Assis et al. 2005). It was the combination of clones with large-scale and efficient hybridisation which led to very high gains in eucalypt productivity – now on an average of 45 m^3 ha^{-1} $year^{-1}$ in that country and several others (Assis 2006, Assis 2011, Assis et al. 2015, Assis 2014, Rezende et al. 2014) at rotation age (6–7 years) in *Eucalyptus* and more recently in *Corymbia* (Assis 2020) as well.

Native forests, including vigorous vegetation in the high rainfall and humidity equatorial regions, have a mean annual increment from 1–5 m^3 ha^{-1} $year^{-1}$ (Payn et al. 2015). Therefore, the high productivity of eucalypts in sub-tropical regions (45–60 m^3 ha^{-1} $year^{-1}$) presents a strong argument for planting them in the areas where they are well adapted, while at the same time, being an important factor at saving the native forests from further destruction and depletion (Evans 2009, Buongiorno & Zhu 2014). Destruction and depletion of native forests is not usually done to establish high-productivity planted forests, but there are demographic and economic reasons why destruction still happens. Evans (2009) estimated that planted forests around the world potentially contributed two thirds of the industrial wood and fibre supply and that 70% of the world's forest products are sourced from 7% of the world's forests - the planted ones. Sub-tropical eucalypts contribute a very substantial part to this production, with an increasing trend.

Planted forests are expanding at a rate of 0.8–1.2 million ha per year in the world and will continue at this rate in the coming decades (Elias & Boucher 2014). These authors stated that "the warm and wet tropics where trees can grow virtually year-round are an important region for fast wood monocultures". A similar conclusion was reached by Álvares et al. (2011). The authors used the 3-PG (Physiological Processes Predicting Growth) model for all of Brazil, in which they considered maximum and minimum temperature data, relative humidity, solar radiation, relief and slope, soil natural fertility, rainfall and soil water holding capacity. Eucalypt productivity is most strongly related to annual rainfall. The authors also predicted a possible productivity of over 45 m^3 ha^{-1} $year^{-1}$ in the vast Amazon area - climates Af and Am (tropical rainforest and tropical monsoon) in the Köppen-Geiger climate classification (Kottek et al. 2006). The same model (3-PG) was used by Behling et al. (2011) at one edge of the Amazon area in Am climate (tropical monsoon) examining one clone of *E. urophylla* and another of *E. pellita*, and they concluded that the current productivity of 20 m^3 ha^{-1} $year^{-1}$ could be increased to 30 m^3 ha^{-1} $year^{-1}$ if appropriate measures of weeding and fertilisation practices are used.

Climate seems to be changing. Predictions (Elli et al. 2020) using the APSIM next generation Eucalyptus model indicated that rainfall in the north (Amazonia and Northeast Brazil) would diminish, but temperature and CO_2 levels would increase, thus affecting productivity. Gustafson et al. (2017) calculated that a moderate increase of 3 ˚C might improve productivity in some species, but a 6 ˚C increase would be detrimental because it is offset by higher respiration and transpiration and also by a higher stomatal CO_2 conductance resistance. Up to a certain degree, higher CO_2 levels could improve productivity, provided that precipitation also increases. It is predicted that the precipitation would come in shorter, stronger bursts than currently, with more dry periods in between. If these predictions also apply to all the other equatorial hot, humid climates (Af and Am) is not clear.

Harwood (2011) provided an approximate range of annual temperature for good growth in plantations for the nine eucalypt species mostly planted around the world. This is described in Table 1.

The table shows clearly that the species which evolved in warmer climates also demand warmer climates in plantation, as is the case of *E. urophylla*, *E. pellita*, *E. tereticornis* and *E. camaldulensis* from northern provenances. Species which evolved in southern, colder climates, also require cooler temperatures in plantations, such as *E. globulus* and *E. nitens*. The other species, coming from intermediate areas demand intermediate temperatures. Most of the provenances of these species come from a range of temperatures, and it is expected that the provenances behave according to their origin. *E. dunnii* has a small natural distribution, partly matching that of *E. grandis*, and needs a similar temperature range in plantation as that species.

The climate in the species' native range gives us a clue as to which species can be planted in similar climates elsewhere. However, precipitation and temperature taken as means can be misleading. Thus, northern *E. camaldulensis*, *E. tereticornis*, *E. urophylla* and *E. pellita* demand approximately similar temperature conditions, but depending on their provenance, they come from widely differing precipitation regimes, which must be matched with those of the plantation sites as close as possible. Queiroz et al. (2020) examined the thermal requirements for optimum growth of hybrid clones, confirming that the hybrids of species originating from of the most tropical areas (*E. urophylla* × *E. grandis; E. grandis* × *E. camaldulensis* and *E. urophylla* × *E. tereticornis*) also require the warmest temperatures for growth when compared with others originating from more temperate species. In addition to precipitation means and temperature means,

Table 1 Approximate range of mean annual temperature for good eucalypt production in plantations

Species	Approximate range of mean annual temperature ˚C for good production in plantations
E. camaldulensis	18–28 (from northern provenances)
E. dunnii	14–22
E. globulus	9–18
E. grandis	14–25
E. nitens	9–18
E. pellita	20–27
E. saligna	14–23
E. tereticornis	17–27
E. urophylla	18–28

it is important to verify if a species evolved in an area with a dry season, e.g., if it comes from Af or Am climate, and also if there is a cooler period in between or not. Constant rains lead to many diseases, especially leaf blights. An interval without or little rainfall is important for some species to withstand or recover from fungal attacks and it is also crucial for eliciting the flowering period of most species.

Climate and soil conditions in humid equatorial areas

Köppen-Geiger classified equatorial climates into Equatorial rainforest, fully humid; Equatorial monsoon; Equatorial savannah with dry summer and Equatorial savannah with dry winter (Kottek et al. 2006). This paper discusses the first two climates, Af and Am, because it is the growth preference for *Acacia mangium* and because Af is the predominant climate in Sarawak. The criteria given by Köppen (Kottek et al. 2006) are as follows:

Type	Description	Criterion
A	Equatorial climates	Temp. min ≥ + 18 °C
Af	Equatorial rainforest, fully humid	Prec. min ≥ 60 mm
Am	Equatorial monsoon	Prec. ann ≥ 25 (100–Prec. min)

Altitude has a strong effect on eucalypts. As elevations increase, there may be a period of lower temperature and drier period as well. Some eucalypts of tropical areas but from elevation like most *E. urophylla* provenances (400–2000 m) (Dvorak et al. 2018) are well adapted to sub-tropical climates and climates similar to their origin, due to the cooler dry period they experience there. Conversely, they are not so well adapted to constant rains, high humidity, and high temperature at the equator and at low elevation, where they tend to be susceptible to leaf blights.

Soils in the equatorial regions vary widely. In some countries, there may be alluvial soils or even those of volcanic origin. But the majority of the soils in wet equatorial regions belong to the much-leached ultisols and oxysols, often with high clay content or sandy clay and low porosity and therefore, poor aeration as are most soils in Sarawak. Such soils often present a low pH, low CEC and severe nutrient deficiencies. The equatorial regions are frequently characterised by high humidity, high and frequent rains with (Am climate) or without a dry season (Af climate), and predominantly poor, leached soils.

The majority of soils in which eucalypts are typically planted in Sarawak are red-yellow podzolics, with a texture from sandy clay loam at the surface to clay subsoil, and they often display similar properties as shown in Table 2 and 3.

No ideal situation of the nutrients in the soil can be given since they depend on many other physical and chemical components of the soil. The above pH is rather low but acceptable for many eucalypt species. The Cation Exchange Capacity is generally low, but the available phosphorus is extremely low, and the iron content could be a problem, depending on pH. While the soil analysis gives us a general idea about the fertility, it is finally the leaf analysis which shows how well the trees perform. Consider the foliar diagnosis as a soil analysis using the plant as an extracting agent (Villar 2007). However, a foliar analysis also has to be compared to what the ideal situation of a totally healthy tree should be in order to evaluate the analysis. Below is a leaf analysis of *E. pellita* with all macro- and micro-nutrients the plant needs (except for sulphur) in the soil as described in Table 3 and what the ideal situation should be in fully expanded leaves in the field (Malavolta et al. 1997).

All macronutrients given are low, except for Mg. The low micronutrients are B, Cu and Fe. Extremely deficient is phosphorus. It is really interesting that with some fertilisation at planting, trees of *E. pellita* and to some degree also *E. deglupta*, do quite well under these conditions, which attests to their extraordinary adaptability to this climate and soil. However, they also do respond very well to phosphorus fertilisation. Still, fertilisation needs to be better studied in each of the different kinds of soil available.

Soil types have a strong bearing on plantation trees. Acacias generally are less demanding than are eucalypts on soil fertility, moreover they fix nitrogen. This implies that a nitrogen fertilisation scheme may be less important for acacias than for eucalypts. It also means that eucalypts have to be planted on better soils than acacias, may exhaust nutrients quicker through successive rotations if not fertilised properly, especially if their bark or even foliage is removed

Table 2 Soil properties of a red-yellow podzolic soil in Sarawak, where eucalypts are planted

Factor	25 cm depth	50 cm depth
pH	3.6	3.6
N %	0.06	0.04
Total P ppm	66	66
Available P ppm	1	1
Total B ppm	8	5
Iron ppm	10,385	12,137
Exchangeable cations		
Exch. K meq %	0.09	0.07
Exch. Ca meq %	0.33	0.29
Exch. Mg meq %	0.06	0.05
C.E.C. meq %	5.51	4.24
Particle size		
Fine sand %	58.08	55.13
Coarse sand %	2.13	0.78
Clay %	21.37	26.72
Silt %	18.42	17.36

Table 3 Foliar analyses of *E. pellita* in typical situations in Sarawak and ideal levels of nutrients

Nutrient	Levels found	Ideal levels
Macronutrients (g kg^{-1})		
N	6.1–12.1	21–23
P	0.20–0.53	1.3–1.4
K	4.1–5.0	9–10
Ca	2.2–4.0	5–6
Mg	1.7–3.5	2.5–3.0
S	–	1.5–2.5
Micronuntrients (mg kg^{-1})		
B	16–23	25–30
Cu	1–2	7–10
Fe	29–46	100–140
Mn	177–390	300–400
Zn	7–12	12–17

with harvested wood. Phosphorus plays a most important role for both genera. Ultisols and oxysols are poor in phosphorus, the clayey nature immobilises much of the soil phosphorus, but this is the element to which both genera respond mostly by fertilisation (Inail et al. 2019) with vigorous growth. Similarly, under sub-tropical conditions but soils rich in Al and Fe which also prevent P uptake, eucalypts respond with considerable growth to P fertilization (Gonçalves 1995), as they do to liming. There are more nutrients in which equatorial soils are often deficient, such as N, K, Ca, Cu, Fe and Zn and frequently B. With successive harvests and depending on which parts of the trees are exported as well as depending on fertilisation management, deficiencies can be expected to worsen after some rotations.

Eucalypt species adapted and native to equatorial conditions

Harwood's recommendations of low-cost alternatives for small-scale planting programmes are useful for the introduction of new species: first, test few of the most likely species to succeed; second, test 1-3 provenances of it with at least 5 parent trees; and third, establish a Seed Production Area (SPA) with these (Harwood 2011). The species adapted to the equatorial conditions are those which evolved under such conditions or close to them. However, there are only a few species which have evolved under such conditions. They include those native to Papua-Indonesia and PNG, but may include some provenances from the north of Cape York Peninsula and northern tips of the Northern Territory in Australia, and even the lowland eucalypts growing on the Lesser Sunda Islands in Indonesia and Timor Leste. The species are listed in Table 4.

The current classification of the genus *Eucalyptus* (Nicolle 2019) places the above species and others which could be useful for hybridisation for equatorial climates into sub-genera, sections, series, subseries and species as in Table 5.

Generally, the section *Latoangulatae* includes most of the species planted in subtropical and tropical climates. The section *Exsertaria* is often represented by species with deep roots and adaptation to poor soils, temporary waterlogging and dry conditions. The section *Maidenaria* is mostly from the south of Australia and includes the cold-resistant species and some may have excellent pulping qualities. Section *Equatoria* is also important here since it includes *E. deglupta*.

Species naturally adapted to Af climate

Eucalyptus pellita, *E. deglupta*, *E. brassiana*, *E. tereticornis* var. *tereticornis* are the better-known ones among the species discussed above. They grow tall and display a good form. Lesser known is *E. leptophleba*. Some species have frequently been tested in Sarawak and elsewhere: *E. deglupta*, *E. pellita*, *E. brassiana*, *E. tereticornis* var. *tereticornis* and frequently *E. urophylla*, which however does not originate from Af climate. The best growth is usually attained by *E. pellita*, which is from Papua Island. *E. brassiana*, *E. deglupta* and *E. tereticornis* var. *tereticornis* can grow well but it depends on their provenance and careful testing. It would be best if seeds of these species can be secured from Papua Island provenances, which often are not easy to obtain.

The two species *E. pellita* and *E. deglupta* are well known as suitable for Af climates, like in Sarawak. They probably constitute the main sources of genetic material for this climate, also in hybrid combinations among them or with other species listed in Table 5. These species will probably constitute the initial basis for tree improvement and hybridisation in the near future in hot, humid climates.

Eucalyptus pellita

Eucalyptus pellita has been the species of choice thus far, to replace *Acacia mangium* where this has been done, especially in Indonesia and Malaysia (Zaiton et al. 2018). It is very important to choose the right provenance and not surprisingly, the provenances of Papua Island have been the best for Af climates in Indonesia, Malaysia and the Amazon area of

Table 4 Species adapted to Tropical rainforest (Af) and Tropical monsoon (Am) climates

Species	Preferred provenances for Af and Am climates
E. pellita	Papua, Northern Queensland
E. deglupta	PNG, New Britain and Mindanao. Others are not well known
E. leptophleba	The species has been little tested
E. brassiana	Papua
E. tereticornis var. tereticornis	Papua
E. alba var. alba	Small species, Lowland Sunda islands
E. urophylla	Possibly some provenances of lowest altitudes
E. orophila	Small species, Lowland Sunda Islands
E. wetarensis	Small species, Lowland Sunda Islands

Table 5 Subdivision of some *Eucalyptus* species in the Subgenus *Symphyomyrtus*, (adapted from Nicolle 2019) for species plantations or hybrid combinations

Subgenus	Section	Series	Subseries	Species
Symphyomyrtus	*Latoangulatae*	*Robustae*		*urophylla*
"	"	"		*orophila*
"	"	"		*wetarensis*
"	"	"		*biterranea*
"	"	"		*pellita*
"	"	"		*robusta*
"	"	*Annulares*		*resinifera*
"	"	*Transversae*		*botryoides*
"	"	"		*saligna*
"	"	"		*grandis*
"	*Equatoria*			*deglupta*
"	*Adnataria*	*Striolatae*		*leptophleba*
"	*Adnataria*	*Siderophloiae*		*paniculata*
"	*Pumilio*	*Pumilae*		*punctata*
"	"	"		*longirostrata*
"	"	*Connexentes*		*propinqua*
"	*Exsertaria*	*Exsertae*	*Subexsertae*	*alba*
"	"	"		*exserta*
"	"	"	"	*brassiana*
"	"	"	*Erythroxylon*	*tereticornis ssp. tereticornis*
"	"	"	*Rostratae*	*camaldulensis*
"	*Maidenaria*	*Deaneanae*		*deanei*
"	"	*Remanentes*		*nitens*
"	"	*Globulares*	*Euglobulares*	*globulus*
"	"	"	"	*bicostata*
"	"	"	"	*pseudoglobulus*
"	"	"	"	*maidenii*
"	"	*Bridgesianae*		*dunnii*
"	"	*Viminales*	*Lanceolatae*	*viminalis*
"	"	"	"	*benthamii*
"	"	"	"	*macarthurii*

Brazil. Wood density is usually around 650 kg m^{-3} at age 5 years and above, tending to increase with age. The wood has many uses, for pulp as well as for solid wood (Harwood 2018). In Papua it may have gone through some generations of in-breeding and selection for tolerance of in-breeding, probably due to small natural population sizes (House & Bell 1996). This may be the reason why it had produced trees tolerant of up to 50% selfing while still yielding viable, vigorous off-spring - an unusual situation in most eucalypt species. Eucalypt species generally are not tolerant to more than 10% selfing, and when it occurs, it manifests itself in immediate inbreeding depression, following which selection eliminates most of the inbreds from the breeding population. The inbreeding tolerance of *E. pellita* leads to a quick increase in the seedlings from seed orchards, where outbreeding is the rule because several provenances and individuals are included. In subsequent generations, there may not be as much progress as in the first generation of outcrossing. Brawner et al. (2010) reported that *E. pellita* from the Kirrama Range and Kuranda in

Queensland performed very well on a highland trial in Sumatra. Therefore, these provenances are very valuable and can contribute genetic variation to a breeding population. Moreover, the Kuranda provenance has a particularly high outcrossing rate, a factor of high significance for any breeding programme with this species.

Some of the best productivity attained is 20.14 m^3 ha^{-1} $year^{-1}$ at age 5.8 years; commonly above 10 m^3 ha^{-1} $year^{-1}$, but higher productivity has been achieved in Indonesia by outbreeding and clonal forestry when only the best clones are used instead of seeds from the first generation. Much more gain can be expected with interspecific hybridisation and cloning.

Eucalyptus deglupta

The *E. deglupta* tests have often been disappointing. However, this species displays excellent growth and resistance to leaf blights in high humidity and warm conditions. The reasons for non-approval probably lies in the fact that wide provenance testing and subsequent clone selection were not done. Since it also has low wood density (varying from 250–400 kg m^{-3}) it may have been of little interest for certain uses. Its wood hardly splits. The provenances vary widely from PNG, New Britain, Seram Island, Sulawesi Island and Mindanao (Davidson et al. 2018). Seeds are available from PNG and Mindanao as well as from an active breeding programme in Solomon Islands. In these environments, some selections, establishment of Seed Production Areas or Seed Orchards have been undertaken in the past. The intermediate provenances from close to the equator (Seram and Sulawesi) are sadly missing everywhere. This is a serious gap in the seed collections and testing which need to be addressed quickly as the natural forests of the species may be endangered.

The current research results suggest that the species usually yield an MAI of over 20 m^3 ha^{-1} $year^{-1}$ up to 47.11 m^3 ha^{-1} $year^{-1}$ in Sarawak in small 300 m^2 year trial plots (over 30 trees) at six years of age. On larger blocks, the values are close to 25 m^3 ha^{-1} $year^{-1}$ at that age.

Eucalyptus brassiana

Eucalyptus brassiana is superbly adapted to the equatorial climate, especially the provenances from PNG and Papua Indonesia, but more testing with Australian provenances is warranted. This species has some very desirable characteristics like high wood density, which is important for many uses when solid wood is needed (Boland et al. 2006). It belongs to the section *Exsertaria* within the subgenus *Symphyomyrtus*. This section has representatives which are often well adapted to poor soil conditions, and which renders them attractive for most equatorial situations, at a minimum as hybrid partners. Many species of this section are also susceptible to the *Leptocybe invasa* gall wasp as well as to several other insects in areas in South America and Africa. However, this susceptibility is extremely variable with many individuals tolerant or resistant to the pests, and this is an important aspect to have in mind when choosing the right provenance as well as individuals within the provenances. Since many insects attacking eucalypts have rapidly spread in most continents, resistance has to be considered when testing, planting and hybridising. Productivity is not known to the author at this time, but hybrids of *E. pellita* × *E. brassiana* seem to perform very well both in Indonesia (Winarmi et al. 2021) and in Sarawak.

Eucalyptus tereticornis var. *tereticornis*

This species also belongs to the section *Exsertaria* and this means it displays the same susceptibility to *Lebtocybe invasa*, but again with individual variability so that resistant specimens are found. It is also known for its adaptation to poor soils and quick growth as many species within this section possibly due to a deep tap root. It is adaptable to dry and seasonally waterlogged conditions like *E. brassiana* and *E. camaldulensis* (Trees for Farm Forestry 2009). One of its main values resides in its use for hybridisation. It has been planted in northern Brazil, Maranhão State, Am climate where the soil is poor and sandy. This is because it maintains good growth and is of high *Leptocybe*-tolerance and has high wood density (Morais 2021). While it is important to have a programme for its genetic improvement and land-race formation, its main potential may lie in hybrid combinations. Therefore, an aggressive hybridisation programme with this and other species is needed for Af climates.

Eucalyptus leptophleba

Eucalyptus leptophleba is native to Western Province of Papua New Guinea and the northern part of

York Peninsula. Therefore, it is considered well adapted to equatorial conditions though it is not well known and is of medium growth on good sites (Boland et al. 2006). Its performance in plantations has not been well assessed and the use of *Eucalyptus leptophleba* depends on further research. Furthermore, botanically it belongs to the section *Adnataria*. This same section includes *E. paniculata*, planted widely in Brazil where straight timber of high-density wood is in demand, and it grows well under subtropical conditions. Hybrids of *E. paniculata* have not yet been produced, although there are trials currently under way in Brazil. Anecdotal evidence suggests *Adnataria* species do not easily hybridise with many species in other sections of *Symphyomyrtus* subgenus, but concrete information is still lacking. Therefore, *E. leptophleba* has to be tested in order to assess its performance under the equatorial Af climate and if it can be used to produce viable hybrids with other adapted species.

The need for provenances and land-races

Plant populations native to their environment are generally well adapted to the vagaries of weather and climate. However, when introduced to new areas, even if they grow well, their adaptation is still not present for all characters. Artificial selection under the new conditions results in adapted trees with the characteristics needed for human use, such as straight growth, resistance to certain pests and diseases and wood of desired qualities which are a result of the best provenances and the best individuals according to commercial interests. Such provenances and selections should form the basis for further tree improvement measures when dealing with an exotic species and result in what is termed "land-races". In the case of equator-adapted species, provenance testing and individual selections for most of the above species are still lacking. Except for spot wise *E. pellita* provenance tests and seed orchards, there are few land-races from the above species established in Af climates. A concerted effort is therefore needed for all interested stakeholders (governments, companies) in obtaining seeds from missing provenances to fill this basic and important gap. Testing, selection of provenances and individuals have to follow. It is imaginable that a country or state government organise collection trips with companies participating by testing, selecting and hybridising. Considering *E. deglupta,* for instance, we know next to nothing about the provenances from Seram and Sulawesi close to and at the equator. Even the provenances from Mindanao in the Philippines after the disappearance of PICOP are threatened, as are some in Papua New Guinea and New Britain. Although the Australian sources of *E. tereticornis* var. *tereticornis* and *E. brassiana* are available and add an important contribution, those of PNG provenance deserve immediate attention and collection effort. The countries in Af and Am climate zones should be most interested in organising new collections of these as they lie at the core of the future of their forestry future.

Species suitable for hybridisation with equator-adapted ones

Interspecific and intraspecific hybridisation can easily be accomplished in the eucalypts, especially using the method called "Artificially Induced Protogyny" (AIP) (Assis et al. 2005). Ease of hybridisation coupled with ease of clonal propagation are the basis for the success of clonal forestry in many countries. The AIP is simple, quick and efficient and has led to the production of a large number of new hybrids. If a pollen from a desired species is not available, it can be imported, such as pollen from *E. globulus* (winter rain areas), into subtropical species growing in Aw areas. In Af climate, most of the subtropical species listed in Table 5 will not develop; they are often attacked by diseases and mostly do not flower to produce pollen. Therefore, hybridising eucalypts in equatorial regions will have to rely on the species listed in Table 4 as flower producers or as seed parents because these usually flower well under such conditions. This means that hybridisation in Af regions will usually involve one parental species, such as *E. pellita*, *E. deglupta*, *E. tereticornis* var. *tereticornis*, *E. brassiana* and possibly *E. leptophleba*. Some of the hybrids among these species have previously proven to be of high interest. PICOP in the 90s for example, produced many *E. deglupta* × *E. pellita* and also *E. deglupta* × *E. urophylla* hybrids which were very successful (Glori 1993) but were mostly lost when PICOP closed down. There have been several efforts to produce hybrids using one or both of the above species in the Brazilian Amazon region, Indonesia, Sabah and Sarawak, and probably more regions. *E. pellita* × *E. brassiana* has been very successfully planted in parts of Indonesia (Winarni et al. 2021), the Amazon and is doing well in Sarawak. Little is known at this time about the other possible hybrids among the equator-adapted species, but they are of high interest for research and forestry development and must form the basis for eucalypt breeding for the equatorial region. It is imperative that these species are well sampled for provenances, tested and bred in these areas as soon as possible. The species listed in Table 4 allow for a wide array of hybrid combinations and there are even more species from subtropical regions and colder areas mentioned in Table 5 which can contribute to an immense wealth of genetic variability. However, the Af climate also means that pollens from the other species have to be imported, and an important network of exchanges between governments, research organisations and companies has to be developed. This should not pose a major hurdle to produce hybrids, but the international regulations to import plant materials are not clear about pollen exchanges. Pollens, unlike seeds, cannot be treated with chemicals, and they often have to be kept cold. However, there are other possibilities. One company in Indonesia has a farm in Bahia State, Brazil (Am climate) where all the hybrids they want to make are produced using their plants and clones in Brazil, while all the pollen from species which do not grow in Indonesia are available in Brazil or elsewhere in South America. The hybrid seeds are then shipped back and tested in Indonesia. This may seem cumbersome, but it is proving to be very efficient.

A description of all the many species which can be used for hybridisation with the equatorial species cannot be given here, but many are included in Table 5. However, it is convenient to point out some of the most promising species for these hybrid combinations which have yielded good hybrid combinations in subtropical areas. They include: *E. urophylla, E. robusta, E. saligna, E. grandis, E. camaldulensis, E. globulus* and *E. dunnii.* A few possibilities are discussed below.

Eucalyptus urophylla is the main component of most hybrids in Brazil, going into over 80% of those produced there (Assis et al. 2015). It is a subtropical species from Lesser Sunda Islands and found in an altitude of 400 to over 2000 masl (Dvorak et al. 2018). Since it grows in areas with a cooler climate and with a pronounced dry season it is well adapted to subtropical conditions with dry winters. Hybrids with *E. deglupta* were produced in Mindanao in the 90s and some of those clones were extraordinary (Glori 1993). It can be expected that the genetic contribution of *E. urophylla* to other hybrids in Af climates will also be good. Similarly, *E. robusta*, *E. saligna* and *E. grandis* and many more could certainly enlarge and contribute well to the gene pool.

Eucalyptus camaldulensis is another species that may contribute to clonal production. While susceptible to leaf blights and several insects, there are many trees not attacked by the insects. A hybrid clone of *E. camaldulensis* × *E. deglupta* called K7 proved to be very successful in Thailand, Laos and Vietnam (Ito 2009). It was later ravaged by *Leptocybe invasa* most probably because the *E. camaldulensis* parent happened to be a susceptible plant. These crosses should be tried using vigorous, disease- and insect-resistant parents. *E. camaldulensis* has the extraordinary advantage of being tolerant of dry conditions, and also of temporarily flooded soils and many individual trees do well in very poor soils. Its hybrids with *E. grandis* have proven to be very productive and resistant to drought and insects in Africa and South America. It is expected that hybrids of this species (as well as other members of the *Exsertaria* section) will contribute to adaptation and overcoming clayey soils with low nutrient content.

Eucalyptus dunnii is from the section *Maidenaria* and is counted as a "cold-tolerant" species, as many others in this section. However, it grows well in many subtropical situations and has very good wood for pulping. It usually flowers very late, often only after being more than 20 years old. It comes from an area similar to the natural environment of *E. grandis.* If hybrids with equatorial species demand colder climate or not has to be determined after production of these. In Brazil many genes of *E. globulus*, *E. dunnii* and *E. benthamii* were introduced into subtropical species, such as *E. urophylla* and *E. grandis*, resulting in successful clones in the subtropical environment.

There are many different two-way hybrids which can be produced, also 3- and 4-way and backcrosses. In later generations, due to segregation and recombination of genes, the possible genetic makeups are immense. Since hybrids are more difficult to produce in Acacias, the ease of vegetative propagation and the multiple results which can be obtained by hybridisation are an important advantage of *Eucalyptus*, as proven in subtropical climates. Hybridisation with *Eucalyptus* in tropical rainforest climate calls for:

1. Introduction of as many provenances as possible from the species adapted to equatorial conditions.
2. Produce land-races of these by selecting among provenances and individuals;
3. Start breeding programmes with such species;
4. As soon as possible, start hybridising these species and also with pollen from other subtropical species not grown in Af and Am climate.

Cloning of pure successful species and hybrids can be made at any of the above stages for testing and commercial propagation whenever they appear. Therefore, following the above strategy does not mean one has to wait many years for useable clones for plantations. However, it is paramount that a robust long-term research program be established and not be neglected during its course.

Corymbia

This genus is being increasingly planted in the subtropical climates (Cwa – hot summer, dry winter) because it is proving adaptable to many conditions, such as soils and some climate variations while exhibiting wood characteristics with many uses.

According to Nicolle (2019), there are 95 species in the sub-genera *Corymbia* and *Blakella*, with some of the species with potential growth which might adapt well in Af climate as shown in Table 6.

No species in this genus is exclusively extra-Australian, but five species can be found in Australia and Papua-New Guinea: *C. novoguinensis* (possibly *C. clarksoniana*), *C. latifolia*, *C. tessellaris*, *C. papuana* and *C. disjuncta* (Nicole 2019). Many hybrids belonging to the two sub-genera have been produced, while some crosses made with species within the same sub-genus did not produce any viable seed (Dickinson 2007).

One of the most remarkable facts about *Corymbia* is its wide adaptability. *Corymbia citriodora*, a typical species of Cwa climate (warm temperate with dry winter), is grown in the Mediterranean climate of Perth (Cs: warm temperate with dry summer). Such an adaptation from monsoonal to Mediterranean climate is unusual in the genus *Eucalyptus*. *C. ptychocarpa* found in Northern Territory (Cwa) when crossed with *C. ficifolia* from Western Australia (Cs climate) yielded hybrids of ornamental value which have a very

Table 6 Classification of some of the most important species in the subgenus *Corymbia*

Genus	Subgenus	Section	Series	Subseries	Species
Corymbia	*Corymbia*	*Corymbia*	*Trachyphloiae*		*trachyphloia*
"	"	"	*Dorsiventrales*		*ptychocarpa*
"	"	"	*Dorsiventrales*		*polycarpa*
"	"	"	*Dorsiventrales*		*clarksoniana*
"	"	"	*Dorsiventrales*		*intermedia*
"	"	"	*Isobilaterales*	*Peltiformes*	*nesophila*
"	"	"	*Isobilaterales*	"	*bleeseri*
"	"	"	*Isobilaterales*	*Limitaneae*	*erythrophloia*
"	*Blakella*	*Naviculares*			*peltata*
"	"	"			*leichhardtii*
"	"	*Torellianae*			*torelliana*
"	"	*Maculatae*			*citriodora*
"	"	"			*variegata*
"	"	"			*maculata*
"	"	"			*henryi*
"	"	*Abbreviatae*	*Tessellatae*		*tessellaris*
"	"	"	"		*confertiflora*

wide adaptability in Australia. The hybrids of *C. torelliana* with the spotted gums in the section *Maculatae* adapted to climates well beyond the range of either species involved, growing in drier and even colder climates than their parental species. The most common hybrid of these, *C. torelliana* × *C. citriodora* var. *citriodora*, has been successfully planted in Australia, Brazil, Honduras, Venezuela, and West Africa among others. *C. torelliana* as seed parent, or pollen parent, crossed with *C. henryi* has been very successful in South Africa, and these hybrids also grow well in West Africa in a tropical environment. Some *C. torelliana* × *C. citriodora* var. *citriodora* hybrid individuals perform well in South Kalimantan, outperforming even good clones of *E. pellita*. In Australia, the hybrids *C. torelliana* × *C. citriodora* var. *variegata* are being planted widely while in Brazil the hybrids of *C. torelliana* × *C. maculata*, *C. torelliana* × *C. citriodora* var. *variegata*, *C. torelliana* × *C. henryi* are proving even more productive in wood volume than the more common *C. torelliana* × *C. citriodora* var. *citriodora* prevalent in that country (Assis 2020). There these hybrids are widely planted for charcoal production because they are adaptable and display resistance to diseases and some environmental conditions common to *Eucalyptus*; additionally, they have a good resistance to periodical drought and have a wood density around and above 600 kg m^{-3}. In Brazil, currently their main use is for charcoal production. *Corymbia* hybrid wood is: more resistant to decay than most eucalyptus wood, splits much less and usable for most products of solid wood, but also for cellulose.

Initial difficulties in vegetative propagation in *Corymbia* have been overcome by: using *C. torelliana* as mother trees; using shoots from lignotubers; keeping mother plants in closed mini-tunnels (Assis 2020) and using tissue culture from seedlings (Trueman & Richardson 2007). Diseases do affect some *Corymbia*, but a wide variation of tolerances allows for selection, and hybrids are usually more resistant than pure species in exotic environments. Insects also attack them. Some beetles attack *C. citriodora* leaves in West Africa and also the hybrid with *C. torelliana.* Kino pockets are a problem for many uses in *C. citriodora* var. *citriodora*, but these are overcome by hybridisation and selection. Some *Corymbia* hybrids have a high percentage of bark, but this is variable at individual and family levels, allowing for selection to be made for this character (Assis 2020).

The availability of seeds and pollen, genetic affinity and timber value means the hybrids of *C. torelliana* with the spotted gums (*C. citriodora* var. *citriodora*, *C. citriodora* var. *variegata*, *C. maculata* and *C. henryi*) will continue to be the most studied ones for some time. However, there are species of much more tropical origin, which have yet to be tried as pure species and for hybridisation under equatorial conditions. These include *C. nesophila*, *C. polycarpa*, *C. clarksoniana*, *C. intermedia*, *C. tessellaris*, *C. confertiflora*, *C. ptychocarpa*, *C. bleeseri*, *C. erythrophloia*, *C. trachyphloia*, *C. peltata* and *C. leichhardtii*.

CONCLUSION

The mistakes of the past should not be repeated, namely the extensive and exclusive planting of only one species. Acacias still hold promise. Resistance to current diseases in *A. mangium* can be found in other species and hybrids. However, genetic diversity, especially in the genus *Eucalyptus* and *Corymbia* offer additional possibilities. Clonal propagation and a huge variety of genetic combinations in these two genera have only just begun. The success of *Eucalyptus* hybrids combined with clonal propagation in subtropical environments can be repeated in the equatorial environment which has high rainfall and warmth. Results have shown that they can be extremely successful when done properly, even though soil fertility is mostly far from ideal, and diseases ravage many species of subtropical origin in the hot and humid climate. The equator-adapted species cited can form the basis for breeding, with additions from genes from subtropical regions adding a wealth of genetic combinations. Adaptability to equatorial conditions combined with the extraordinary genetic variability found in sub-tropical eucalypts and the ease of hybridisation and cloning offer extraordinary opportunities for plantation forestry in Af and Am climates.

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