Eucalypts for Tropical Rainforest (Af) climate

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Abstract

The equatorial region of the world includes areas of Tropical Rainforest (Af) and Tropical Monsoon (Am) climate zones, which are distinguished by high temperatures and high rainfall, but soils which are often deficient. Potential productivity of plantation forestry in this area is high, and so are the pest and disease dangers which threaten it. This paper describes the *Eucalyptus* and *Corymbia* species which are adapted to this situation and also resistant to the main diseases like leaf blights. Based on the highly adapted *E. biterranea* and *E. deglupta* and several more, hybridization combined with vegetative propagation is discussed as an excellent alternative to obtain quick gains in short rotations while maintaining wide genetic diversity in such plantations. Management remedies are given for the possible backlash of quick soil depletion.

Keywords: *Rainforest climate, Eucalyptus, Corymbia, vegetative propagation, hybridization, adaptation, productivity, plantations*

Table 1
Tropical, arid and temperate climates

1 st letter (vegetation)	2 nd letter (rainfall)	3 rd letter (temperature)
A (tropical)	f (Rainforest)	
	m (Monsoon)	
	w (Savanna, Dry winter)	
	s (Savanna, Dry summer)	
B (arid)	W (Desert)	
	S (Steppe)	
		h (Hot)
		k (Cold)
C (temperate)	w (Dry winter)	
	f (No dry season)	
	s (Dry summer)	
		a (Hot summer)
		b (Warm summer)
		c (Cold summer)

Introduction

Köppen-Geiger classified the climates of the world regarding the vegetation (Table 1). Each climate was defined by three letters: the first defines the kind the plants of each zone (A – equatorial zone; B – arid zone; C – warm temperate zone; D – snow zone; and E – polar zone) the second refers to the precipitation, and the third to the temperature (Kottek et al. 2006).

The Af climate, as defined in the Köppen-Geiger classification (Kottek et al. 2006), is a climate with temperatures always above 18 °C and monthly minimum precipitation above 60 mm (Figure 1). This equatorial climate occurs in several areas around the world, notably in the central and eastern Amazon area, the Guyanas, western Colombia and Panama, central DRC, peninsular Malaysia, the island of Borneo, Sumatra and western Java, Sulawesi and a major part of northern Papua and Papua-New Guinea, New Britain, Solomon Islands and several more Pacific islands, generally spanning latitudes 10° north and south of the equator (Köppen-Geiger classification Map, 2016).

Figure 1

The Köppen-Geiger Classification Map (from <http://koeppen-geiger.vu-wien.ac.at> with the kind permission from Prof. Dr. F. Rubel – 15.3.2021).

The soils are generally weathered and leached ultisols and oxy-sols with severe nutrient deficiencies but can contain fertile volcanic soils and alluvial soils. Areas with these climates generally host luxuriant native vegetation, due to the favourable temperature and abundance of water. Plants which evolve under such conditions usually do not adapt to areas with a clear dry season and/or a period with lower temperatures.

Plant diseases usually thrive under these conditions as well. Co-evolution of plants and parasites may have led to some tolerance or resistance of the plants to the native diseases.

Important crop plants from Af areas have been spread to similar areas around the world, and have become of high importance to many local economies. That is the case of the cacao tree (*Theobroma cacao*), rubber tree (*Hevea brasiliensis*), oil palms (*Elaeis guineensis* and *Elaeis oleifera*) and several banana species (*Musa* spp.).

Thirty-one percent of the global land surface areas are covered with forests – 3.99 billion hectares (Payn et al. 2015); of these 20.1 % are in Russia, 12.2 % in Brazil, 8.5 % in Canada, 7.6 % in USA and 5.4 % in China (FAO 2020). Seven percent – 291 million hectares – (Payn et al. 2015) of the total forests in the world are plantations (Evans 2009, Payn et al. 2015). Evans (2009) estimated that “planted forests contribute massively to industrial wood and fibre supply (potentially two thirds)” and that “Globally, 70 % of forest products are sourced from 7 % of the world’s forest, of which the latter are predominantly

planted”. Buongiorno and Zhu (2014) from data of 2009, calculated that planted forests reduced roundwood harvesting globally from natural forests by 26 %. Brazil alone, aside from the sizable native forest in the Amazon area with Af climate, had 9 million hectares of planted forests in subtropical climates; 77 % was eucalypts with 6.97 million hectares (IBÁ 2020). The percentage of extremely productive clonal eucalypt forests is not certain, but estimates are that it makes up 90 % of eucalypts in that country. Planted forests with their high productivity help save native forests from being further depleted (Evans 2009, Buongiorno and Zhu 2014), even though there are other pressing economic and demographic reasons why these forests are often exploited.

Majer and Recher (1999) warn that large-scale exotic eucalypt plantations can be a threat to the biodiversity and environment. They do believe that fast rotation eucalypt plantations with high productivity are a way of diminishing the pressure on native timber exploitation but should not replace the native forest to such a degree that it becomes minimal, and hypothesize that native trees should be better for a plantation than exotic ones. They recommend that eucalypts in Brazil be planted in such a way as to allow for wildlife corridors between blocks of native forests, as is commonly done in large eucalypt plantations in Brazil. Elias and Boucher (2014) state that fast wood plantations are expanding worldwide at a rate of 0.8-1.2 million hectares/year and will continue to do so over the next decades. They state that “the warm and wet tropics, where

trees can grow virtually year-round, are an important region for fast wood monocultures" and also that clearing of natural forests for wood plantation is limited mostly to Southeast Asia, Indonesia in particular. They argue that by cultivating wood through sustainable forest management techniques, including properly managed plantations, the rise in demand should not affect the world's forests.

While native forest trees around the world commonly grow at a rate of 1-5 m³/ha/year (Payn et al. 2015), in productivity they stay way behind well managed eucalypt plantations in subtropical environments where productivity often exceeds 45 m³/ha/year. There are, of course, other high valued timber trees – native or not - which can do well in plantations, such as the native *Ochroma pyramidale*, balsa-wood in the Amazon area, with a productivity of 17 m³/ha/year in seven year rotations or the introduced *Tectona grandis* in Am climates of Amazonia with 10-15 m³/ha/year which demands good alkaline soils and is grown in 25 year rotations, which have to be thinned with some wood harvested earlier (Barbosa Filho, J. personal communication 2021). These are also produced in monoculture.

Extraordinary advances of productivity were attained in several countries and different climates – generally with a dry season and in subtropical conditions - with the genus *Eucalyptus* and more recently *Corymbia*, by using hybridization in conjunction with clonal propagation.

Hybridization and vegetative propagation are not the only means of genetic tree improvement. Another means which is progressing rapidly is genetic modification (OECD 2014). Considerable progress has recently been made by inserting genes for cold tolerance, salt tolerance, drought tolerance, decrease in lignin content and even disease resistance into eucalypts (OECD 2014). It is likely that for general adaptability, which depends on large gene blocks, traditional tree improvement based on selection and hybridization breeding will continue to be the main strategy.

The high productivity obtained by hybridization and cloning in subtropical regions begs the question if similar methods could not be applied in areas of Af climates as well.

Eucalyptus

Compared with over one thousand acacias in Australia alone, the 730 species of the genus *Eucalyptus* are fewer (Nicolle and Jones 2018) but they include dozens of species with wide adaptability in many climates, while there is only a handful of plantation acacias (Table 2).

The genus *Eucalyptus* includes 470 species within the very large subgenus *Symphyomyrtus*, where most of the planted eucalypts reside, but there are more in different subgenera. *Symphyomyrtus* is divided into 11 sections (Nicolle and Jones 2018). Most planted eucalypts are included within the three sections *Latoangulata*, *Exsertaria* and *Maidenaria*. These sections include eucalypt species for tropical, sub-tropical, arid zone climates, monsoon and Mediterranean areas and cold-hardy ones. Wood qualities also vary; there are very high and low density woods, splitting and non-splitting woods, suitable

for high-grade cellulose and soluble cellulose, energy, charcoal as reducing agents in the iron industry, mine poles and solid wood products. There is an extraordinary wide genotypic and phenotypic variability available.

All eucalypts have 2n= 22 chromosomes and the vast majority of the species in the mentioned three sections can be hybridized with each other, often yielding hybrids with heterosis (Rezende et al. 2014), widening the phenotypic combinations for growth, resistance to different environments and diseases, as well as for wood properties. Interspecific hybridization is no guarantee for heterosis, but can also produce depressed and deformed offspring (Assis 2000, Potts et al. 2003). Therefore trial and selection is always necessary for each hybridization done.

Exclusively extra-Australian species include: *E. binacag*, *E. deglupta*, *E. alba* var. *alba*, *E. sp.*, *E. orophila*, *E. urophylla* and *E. wetarensis*. The differentiation of *E. binacag* in Mindanao from *E. deglupta* is not generally known or accepted.

Australian and Extra-Australian species are: *E. leptophleba*, *E. brassiana*, *E. tereticornis* subsp. *tereticornis*, and *E. biterranea*. The naming of *E. biterranea*, being the north Queensland and PNG provenance of *E. pellita* is not generally known or accepted.

Table 2 includes 90-95 % of the eucalypts used worldwide for plantations either as hybrids or species. They are: *E. camaldulensis*, *E. dunnii*, *E. globulus*, *E. grandis*, *E. nitens*, *E. pellita*, *E. saligna*, *E. tereticornis* and *E. urophylla* (Harwood 2011). The species composition is different, according to the region, purpose or climate, and often includes other species.

Ladiges (1997) established a phylogeny within the accepted six sections by Pryor and Johnson (1971) within the genus *Symphyomyrtus*. That phylogeny pointed to a close relationship between the sections *Latoangulata* (then known as *Transversaria*), *Maidenaria* and *Exsertaria*, a fact which Potts et al. (2003) showed to agree with the many hybrids done among the species in these sections.

Currently Nicolle and Jones (2018) recognize 11 sections within *Symphyomyrtus*. Potts et al. (2003) compiled a list of manipulated hybrids which had been produced between species of the formerly known sections as established by Pryor and Johnson (2011). Table 3 shows that most hybrids were between the sections *Exsertaria*, *Latoangulata* and *Maidenaria*, also between *Maidenaria* and *Adnataria*; *Adnataria* and *Bisectaria*; and *Bisectaria* and *Dumaria*. *Latoangulata* formerly was to a large degree known as *Transversaria*.

The possibility of crosses between the sections not yet made remains open. However, the further the species are separated botanically, the less likely they are to yield hybrids and more likely to produce dwarfs and plants otherwise unfit for growth (Potts et al. 2003). Assis (2000) found that within *Symphyomyrtus*, sections now known as *Latoangulata* (formerly *Transversaria*), *Exsertaria* and *Maidenaria* (Nicolle 2019) hybridize widely with each other, but the closer, the more heterosis one is likely to find, as generally within and between sections *Latoangulata* and *Exsertaria*; while species of *Maidenaria* yield some percentage of dwarfs and other abnormalities when crossed with other species of the same section or with species

Table 2

Subdivision of some *Eucalyptus* species in the Subgenus *Symphyomyrtus*, according to Nicolle (2019)

Subgenus	Section	Series	Subseries	Species
<i>Symphyomyrtus</i>	<i>Latoangulatae</i>	<i>Robustae</i>		<i>urophylla</i>
"	"	"		<i>biterranea</i>
"	"	"		<i>pellita</i>
"	"	"		<i>robusta</i>
"	"	<i>Transversae</i>		<i>saligna</i>
"	"	"		<i>grandis</i>
"	<i>Equatoria</i>			<i>deglupta</i>
"	<i>Exsertaria</i>	<i>Exsertae</i>	<i>Subexsertae</i>	<i>alba</i>
"	"	"	"	<i>brassiana</i>
"	"	"	<i>Erythroxylon</i>	<i>tereticornis</i> ssp. <i>tereticornis</i>
"	"	"	<i>Rostratae</i>	<i>camaldulensis</i>
"	<i>Maidenaria</i>	<i>Remanentes</i>		<i>nitens</i>
"	"	<i>Globulares</i>	<i>Euglobulares</i>	<i>globulus</i>
"	"	"	"	<i>bicostata</i>
"	"	"	"	<i>pseudoglobulus</i>
"	"	"	"	<i>maidenii</i>
"	"	<i>Bridgesianae</i>		<i>dunnii</i>
"	"	<i>Viminalae</i>	<i>Lanceolatae</i>	<i>viminalis</i>
"	"	"	"	<i>benthamii</i>

Table 3

Crosses made between the six sections recognized by Pryor and Johnson (1971) (adapted from Potts et al. 2003)

	<i>Latoangulata</i>	<i>Exsertaria</i>	<i>Bisectaria</i>	<i>Dumaria</i>	<i>Adnataria</i>
<i>Maidenaria</i>	x	x	-	-	x
<i>Latoangulata</i>		x	-	-	-
<i>Exsertaria</i>			x	-	-
<i>Bisectaria</i>				x	x
<i>Dumaria</i>					-

of *Latoangulata*. Still, in the crosses of species from *Maidenaria* with species from *Latoangulata*, among many offspring one finds frequent heterosis for growth (Assis 2000). Hybrid offspring are used in plantations by vegetative propagation, which captures additive and non-additive variance superiority. Dickinson et al. (2007) also found that within *Corymbia*, the closer the species, the higher the seed set and heterosis when hybridizing.

Progress made with vegetative eucalypt propagation was largely established in the last three decades of last century, and is now a technique widely applied everywhere where eucalypts are planted commercially (Assis et al. 2004, Assis 2006, 2011). This technique made it easy to capture and retain heterosis in hybrids, using additive and non-additive variance for mass propagation in plantations (Assis 2004, 2006; Resende et al. 2014, Rezende et al. 2014).

The hermaphroditic and androgynous characters of the *Eucalyptus* flowers are easy to be manipulated for hybridization (Rezende et al. 2014). However, it was the advent of hybridization by the artificially induced protogyny (AIP) (Assis et al. 2005) which stimulated vast programs in eucalypt hybridization. By this method it is easy, quick and very efficient to hybridize

eucalypts (Dickinson et al. 2007), and it was quickly adopted worldwide.

The possibility of hybridization plus the ease of vegetative propagation (Assis et al. 2004, Harwood and Nambiar 2014a) offer an extraordinary opportunity to quickly breed new combinations of characters within the eucalypts with a wide possibility of adaptations. This fact led to many new combinations of characters which in turn is bringing quick progress to eucalypt culture through the production of new clones with heterosis, productivity, disease resistance and desired wood characteristics (Assis et al. 2004, Assis 2006, 2011). Production of many different hybrid combinations associated with testing and later a quick turnover of planted clones in plantations is crucial to obtain a wide array of different genotypes for adaptability associated to specific wood characteristics for the industry and for resistance breeding.

Due to the progress made with hybridization and plant production from minicuttings, eucalypts with high productivity are planted widely around the world in hugely differing climates, such as China, India, Indonesia, South Africa, Brazil, Portugal, Chile, Argentina, Uruguay, and others. Productivity often exceeds 35-45 m³/ha/year, up to 60 m³/ha/year (Rezende et al.

2014). This progress so far has been practically restricted to tropical and subtropical areas of the world, with a dry annual season which many species need to elicit flowering or escaping foliar blights and other diseases.

Planting of species which did not evolve in Af or Am climates makes them susceptible to many diseases when planted in such climates, especially leaf blights (Gonçalves et al. 2013, Rosa personal communication 2020). While the *E. urophylla* x *E. grandis* hybrid clones are very productive in subtropical areas, the majority is not suited for Af and Am climates (Gonçalves et al. 2013). *E. urophylla*, *E. camaldulensis*, *E. tereticornis*, *E. grandis*, most clones of *E. urophylla* x *E. grandis* were all seriously attacked by leaf blights in the Am climate of Amapá, Brazil, even though there is a distinct dry season (Rosa personal communication 2020). In peninsular Malaysia, *E. camaldulensis* planted in the 1980's grew well in the first years, but was totally abandoned in the 1990's due to leaf blights, as happened in Vietnam (Harwood 1998); but survived well in a climate in southern Vietnam with a distinct dry season (Harwood and Nambiar 2014a). In Thailand, in some very wet areas, *E. camaldulensis* succumbed to *Kirramyces destructans* and *Cylindrocladium* sp. leaf blights (Harwood and Nambiar 2014a).

Flowering behaviour is one of the signs of adaptation to a region and is also important for hybridization, although pollen can be transported from other regions. It is under genetic and environmental control with environmental conditions such as photoperiod, stress, a cold spell or a dry season triggering it. There are species which are very late in flowering, such as *E. dunnii*, which even in adequate climates usually flowers only from about age 20 onwards. Most species start flowering around age 3 years. Some other species, like *Corymbia torelliana*, for many years does not flower in Australia, while in Brazil and West Africa it is precocious in flowering and does so profusely every year. Species which in subtropical regions flower abundantly, when transferred to equatorial climates frequently do not (Harwood 1998). Rosa, A. (personal communication, 2020) states that in Amapá, Brazil, most *E. urophylla*, *E. grandis*, clones of *E. urophylla* x *E. grandis* and *E. camaldulensis* do not flower. *E. brassiana* provenances from Australia did not flower, but those from PNG, from a similar climate as in the Amazon, flowered normally. *E. pellita* (actually *E. biterranea*) had a similar behaviour, with PNG provenances showing better adaptation in every sense. It must be stated that among both *E. urophylla* and *E. urophylla* x *E. grandis*, a few clones and individuals are still resistant to diseases and also flower well (Rosa personal communication 2020), which attests to genetic differences among provenances and individual tree combinations. In this resides a source and potential for selection and hybridization for equatorial climates.

Rezende et al. (2014) state that expanding the range of commercial forests is as important as increasing its productivity. For Brazil this would mean advancing plantation forests from the current areas of Tropical savanna with dry winter (Aw); Dry winter humid sub-tropical (Cwa); Dry winter subtropical highland (Cwb); and Humid subtropical (Cfa) climates into the semi-arid Northeast (BSh climate) of the country and into the Amazonian region with Tropical rainforest (Af) and Tropical

Monsoon (Am) climates (Gonçalves et al. 2013). In the Northeast the limiting factor is low rainfall and high temperature, which can to a certain degree be improved by using drought-adapted species as found mainly in the section *Exsertaria* (e.g. *E. camaldulensis*, *E. brassiana* and *E. tereticornis*) as hybrids or pure species, but will not improve productivity over a certain level due to limited rainfall. However, for the Amazonian area, with constant (Af) or monsoonal (Am) rainfall during the year, productivity can be high.

Álvares et al. (2011), using the 3-PG model (Physiological Processes Predicting Growth) advanced predictions based on maximum, mean and minimum temperature data, relative humidity, solar radiation, relief and slope, soil natural fertility, rainfall and soil water holding capacity, of where planted forests would be productive and how much. Annual rainfall was the strongest factor related to productivity. For the semi-arid Northeast, the maximum attainable productivity would be 25 m³/ha/year. But for the Amazonian region with Af and Am climates, which makes up over 40 % of the country, the maximum potential productivity predicted exceeded 45 m³/ha/year. This area has a mean temperature of > 26 °C (Queiroz et al. 2020). This is an extraordinary potential productivity on a very large area. Behling et al. (2011), also using the 3-PG model, predicted that in an area of Am climate at the eastern edge of the Amazon area, the current productivity of two clones (*E. pellita* and *E. urophylla*) could be increased from the current 20 to 30 m³/ha/year, under appropriate fertilization and weed control practices.

Elli et al. (2020), using the APSIM Next Generation *Eucalyptus* model predicted that in future rainfall in the North (Amazonian) and Northeast Brazil would diminish, but temperature would increase everywhere due to current trends in climate change. This would also affect predictions about productivity. CO₂ emissions tend to increase, theoretically improving photosynthesis under a higher temperature, provided that precipitation also increased. Using models to predict landscape change with changing climate, Gustafson et al. (2017) predicted that a moderate increase, up to 3 °C in temperature, might improve productivity of some species, however an increase of 6 °C would be detrimental, as it is offset by higher respiration and transpiration and also by a higher stomatal CO₂ conductance resistance. With an increase of precipitation this might be somewhat mitigated, but predictions are that precipitation would come in short strong bursts with more dry periods in between, leading to less productivity in general, depending on the adaptation of individual species or clones to such a situation.

The mean optimum temperatures for growth of the nine most planted eucalypt species in the world were estimated by Harwood (2011) as given in Table 4.

When examining maximum, mean and minimum temperatures for growth of certain clones of *E. urophylla* x *E. grandis*, *E. grandis* x *E. camaldulensis*, *E. urophylla* x *E. tereticornis* and three clones of *E. benthamii* and one of *E. saligna*, Queiroz et al. (2020) found that optimum mean temperatures for the clones of *E. urophylla* x *E. tereticornis*, *E. grandis* x *E. camaldulensis* and *E. urophylla* x *E. grandis* varied from 18-25 °C. For *E. saligna* it varied

Table 4

Approximate range of mean annual temperature for good growth in plantations - from Harwood (2011)

Species	Approximate range of mean annual temperature (°C) for good growth in plantations
<i>E. camaldulensis</i>	18-28 (northern provenances)
<i>E. dunnii</i>	14-22
<i>E. globulus</i>	9-18
<i>E. grandis</i>	14-25
<i>E. nitens</i>	9-18
<i>E. pellita</i>	20-27
<i>E. saligna</i>	14-23
<i>E. tereticornis</i>	17-27
<i>E. urophylla</i>	18-28

from 13 – 24 °C, and for the *E. benthamii* clones from 11-24 °C. These temperatures are in good agreement with Harwood's estimates who did not include *E. benthamii*; a species adapted to colder climates.

With mean temperatures above 26 °C, even over 30 °C, equatorial Af and Am climates are not suitable for the hybrids given above, as the species and clones mentioned earlier find their optimum mean growth temperatures below this level and are adapted to a climate with a pronounced dry and/or cooler period. Productivity depends on the plants being healthy as well. However, a constantly wet, humid and hot situation leads to susceptibility to many diseases, especially leaf blights and *Chrysoporthe cubensis* in eucalypts (Harwood 1998, Harwood and Nambiar 2014a). Therefore, predictions about productivity in areas where species and clones are not satisfied as to climate requirements and disease resistances must be viewed critically. For hot and humid environments (Af and Am climates), species and clones adapted to those conditions must first be found or developed.

Assis (2015) mentions the following diseases and species resistant to them:

- *Puccinia psidii*: *C. torelliana*, *E. camaldulensis*, *E. microcorys*, *E. pellita*, *E. pilularis*, *E. propinqua*, *E. resinifera*, *E. robusta*, *E. saligna*, *E. tereticornis* and *E. urophylla*;
- *Cylindrocladium* sp. in northern Brazil: *E. pellita*, *E. robusta* and *E. resinifera*;
- *Chrysoporthe cubensis*: *C. citriodora*, *C. torelliana*, *E. cloeziana*, *E. pilularis*, *E. paniculata*, *E. pellita*, *E. urophylla* and *E. robusta*.

Many of these species are not adapted to equatorial climates, where resistance to the diseases may break down while susceptibility to new ones can appear. Species which evolved in equatorial climates will better resist wet, hot conditions and adapt easier to increasing temperatures.

Therefore, in order to obtain highly productive and resistant eucalypts for equatorial climates a simple transfer of clones from subtropical areas is not sufficient; active breeding for such areas has to be done.

The species which evolved in Af climates and are superbly adapted to these conditions in growth and disease resistance are especially *E. biterranea* ("*E. pellita*" from PNG) and *E. deglupta*. In addition, *E. brassiana*, *E. tereticornis* var. *tereticornis*, *E. alba*

var. *alba* and *E. leptophleba* are good candidates. *E. urophylla*, *E. wetarensis* and *E. orophila* stem from areas with a definite dry season or of higher elevations, but through hybridization can contribute adaptive genes to hot humid environments as well, as can the many species and clones now used in subtropical conditions.

***Eucalyptus biterranea* (*E. pellita* from north Queensland and Papua)**

The northern Qld and PNG provenance of this species is referred to as *E. biterranea*, having been separated from *E. pellita* by Hill and Johnson (2000), based on morphology and molecular characters. It includes the "*E. pellita*" from northern Queensland, approximately north of 15°S and PNG provenances. House and Bell (1996) separated *E. scias* from *E. pellita* by isozyme studies, but saw no reason at that time to divide *E. pellita* into *E. pellita* and *E. biterranea*. For convenience, here we speak of *E. biterranea* or *E. pellita* from north Queensland and PNG as being the same species. It is classified as being part of the sub-genus *Symphyomyrtus*, section *Latoangulata*, series *Robustae*, joining *E. urophylla*, *E. pellita* and *E. robusta* (Nicolle 2019). The section *Latoangulata*, series *Transversae* includes the well-known species *E. saligna* and *E. grandis* (Nicolle 2019). All of these species can easily be hybridized with each other often resulting in considerable heterosis.

E. biterranea from PNG is well adapted to Af and to Am climates, and is resistant to a range of tropical diseases (Harwood and Nambiar 2014a). After *Ceratocystis* wilt decimated acacia plantations in Southeast Asia, it is the preferred species for planting, growing well in Indonesia, Malaysia and the Amazon area. At age 5 years in Sabah on Borneo Island it had a density of 629 kg/m³ (Japarudin et al. 2020). In the Amazon area it is a preferred species for planting and for hybridization (Rosa, A. personal communication 2020). In all these areas *E. pellita* from PNG or *E. biterranea*, outperforms *E. pellita* from Australia. It usually occurs on lowland in rainfall areas of 1,000-3,000 mm a year with dry seasons varying from 0-5 months and an altitude of 0-800 m asl (Harwood 2018). A remarkable fact for the breeder is that the PNG provenances often have a high degree of inbreeding, with outcrossing around 50 % (House and Bell 1996, Harwood 2018). This is unusual in the eucalypts, which

normally have an outcrossing rate of 70 % to over 90 %. The fairly low outcrossing rate in the original populations may be due to the small isolated populations which underwent inbreeding. Hence, a considerable genetic gain in the first generation of improvement can be due to outcrossing which occurs in the seed orchards. In subsequent generations of improvement the gains obtained by outcrossing will probably be lower.

Since *E. biterranea* (or northern Queensland and PNG *E. pellita*) evolved and thrives in equatorial climates, it is much better equipped to cope with the higher temperatures, humidity and diseases common in these environments, than are the species used in subtropical regions, which need lower temperature means and a definite dry season. This is being attested widely in Indonesia, Malaysia, and Vietnam and in the Amazon area. However, hybridization with many of the species from subtropical regions, such as *E. urophylla*, *E. grandis*, *E. brassiana*, *E. camaldulensis*, *E. tereticornis* etc. and their hybrids will infuse useful genes for improving productivity and add to specialized uses of the wood. While *E. biterranea* is easy to root from coppice shoots, it does have a sizable amount of bark (8-14 %), which can be improved through selection and hybridization. Therefore, *E. biterranea* will be one of the main species and partner for hybridization for Af and also Am climates, if the productivity hypothesized for hot and humid environments (Álvarez et al. 2011) is to be achieved.

E. biterranea is not free of diseases. *Ceratocystis fimbriata* has in a few cases been found in Southeast Asia on *E. biterranea*. Arseni et al. (2016) in East Kalimantan found several leaf diseases associated to *E. biterranea*, but none of them damaging the trees. However, attention with pests and diseases is warranted.

Eucalyptus deglupta

This species, also belonging to the subgenus *Symphyomyrtus*, is placed into the section *Equatoria* by Nicolle (2019), where it stands alone or, if one accepts this division, together with *E. binacag*. In the present paper *E. deglupta* and *E. binacag* will be treated as being one species.

E. deglupta has a much wider natural distribution than does *E. biterranea*. It spans "between tropical latitudes from 9°N to 11°S in a markedly discontinuous distribution through eastern and southern Mindanao in the Philippines, Sulawesi, northern coast of Seram Island, West Papua and Papua provinces, PNG including West Sepik Province, central highlands, eastern coastal lowlands of the mainland and most of the island of New Britain" (Davidson et al. 2018). The full altitudinal range is from sea level to 2,500 m asl and annual rainfall distribution of 2,500-5,000 mm, growing best on alluvial soils and below 150 m asl, but also on volcanic ash (Davidson et al. 2018, Davidson, J. personal communication 2020). *E. deglupta* grows to 60 m in height, and can reach 80 m with 3 m dbh, is cylindrical and self-pruning, often with buttresses (Davidson et al. 2018). With such a diverse and discontinuous distribution, it is expected that there are differences between the many possible provenances. Cossalter (1975) examined and characterized 30 provenances on the island of Sulawesi and 10 on Seram. On Sulawesi the

species crosses the equator, being the only eucalypt species native north of the equator, up to Mindanao in the Philippines. The wood is of low density in plantations, from 300-400 kg/m³, increasing in density with age. The wood usually does not split. Bark is very thin, about 2 mm thick, shedding off in small flakes which gives the trunk a multi-colored aspect and hence the species is often referred to as "rainbow gum" or Mindanao gum. Due to the thin bark it is very fire sensitive. The wood is used for furniture, flooring and many purposes, including for a strong sulphate paper (Davidson et al. 2018). The species is not easy to graft or to coppice when cut down. When girdled, shoots are usually produced in lower numbers than for other species but the shoots are easy to propagate by vegetative means. Air-layering for establishment of clonal seed orchards works very well. Even though in its native habitat it is rarely exposed to more than three dry months (Cossalter 1975); in Ghana it thrived and withstood severe droughts of five to six months. Chaplin (1993) states that on the Solomon Islands this species has a MAI between 20 and 40 m³/ha/year.

Vigneron et al. (2000) report that the crosses *E. pellita* x *E. deglupta* and *E. urophylla* x *E. deglupta* produced mostly dwarfs. In the 1990's a breeding program in Mindanao was quite successful, and excellent hybrids were produced with *E. urophylla* and *E. pellita* (*E. biterranea*?) (Glori, 1993), increasing wood density and showing resistance to the varicose borer (*Agrilus sexig-natus*), leaf blights and kino veins.

Due to the small size of the *E. deglupta* flower buds, the species is recommended to be used as the seed parent, as its pollen tubes might not reach the ovaries in the styles of larger-flowered eucalypts. However, in the Philippines they claimed to have obtained crosses in both ways with *E. pellita*; using *E. deglupta* as seed bearer and as pollen donor as well (Glori 1993). It is not clear if in the Congo the same hybrids were produced with *E. deglupta* as pollen donor.

In spite of *E. deglupta* standing as the only representative in the section *Equatoria* (Nicolle 2019) it seems to easily produce hybrids with several other representatives in *Symphyomyrtus*. A spontaneous hybrid with *E. camaldulensis* which occurred in Thailand, called K7, was very successful there, in Laos (Ito 2009) and Vietnam. It had a wood density of 490 kg/m³, better fiber qualities than *E. camaldulensis* and withstood droughts of 5 months (Ito 2009). Later it proved susceptible to the introduced gall wasp *Leptocybe invasa* and was eliminated (Harwood and Nambiar 2014a). Since *E. camaldulensis* belongs to the section *Exsertaria*, this indicates wide possibilities of crosses of *E. deglupta* with other species of sections in the subgenus *Symphyomyrtus*.

Being such a superbly adapted species to the humid equatorial climates, it is surprising to see plantations mainly confined to the Philippines, Papua-New Guinea and Solomon Islands. One reason may be its relative low wood density, but probably other areas where it can grow well, such as the vast Amazon area, Congo, Indonesia and Malaysia, did not test a wide range of provenances and did not consider the species because they tried only one or two provenances which happened to be unsuccessful. Some provenances are difficult to come by, such as Sulawesi, Seram and West Sepik, because

seed collections were not made or not made available. Material from the Philippines, Papua-New Guinea and New Britain are easier to obtain. The resistance this species has to leaf blights, high humidity and temperatures are very advantageous (Davidson et al. 2018). Extraordinary hybrids have been produced earlier with considerable variation and increase in wood density (Glori 1993) and the ease to now do it through artificially induced protogyny, makes it extremely attractive for hybridization when plantations are considered for Af and Am climate zones.

Eucalyptus tereticornis* var. *tereticornis

E. tereticornis var. *tereticornis*, belonging to the section *Exsertaria*, series *Exsertae*, subseries *Erythroxyton* (Nicolle 2019), has a wide latitudinal range in Australia, on the east coast from southern NSW into Cape York Peninsula in Queensland (Boland et al. 2006). But it also occurs in PNG, where the most promising provenances for Af and Am climates occur. This tree is easy to reproduce from coppice shoots and hybridizes easily with other species of the sections *Exsertaria*, *Latoangulata* and *Maidenaria*. In Am climates the PNG provenances have been performing especially well (Morais, E.J., personal communication 2021). Being from medium-sized up to 50 m tall on favourable sites, it can tolerate several months of flooding as well (Boland et al. 2006). In plantations its wood can reach a better density than does *E. urophylla* or *E. grandis*, but it is quite susceptible to *L. invasa*. In spite of this susceptibility, vigorous individuals were found, growing well and not attacked by the gall wasp (Morais, E.J., personal communication, 2021) in an area of Am climate.

Especially if seed from PNG can be secured, it is a very good candidate for the Af and Am climates, both as a pure species and also as a hybrid partner. A breeding program for this species is important to be started in Af or Am climates, where it can withstand the high temperatures and high humidity.

Eucalyptus brassiana

E. brassiana is another representative of the section *Exsertaria*, series *Exsertae*, and subseries *Subexsertae*, therefore closely related to *E. tereticornis* var. *tereticornis* and also to *E. camaldulensis*. This species occurs in Queensland, on the north-eastern coast of Cape York Peninsula, on Horn Island and in PNG (Euclid – online edition, 2020). In plantations in Brazil in an Am/Aw climate adjoining the Amazon area and on poor soils, selected trees at 9 years had a density of 608-620 kg/m³ (Morais, E.J., personal communication, 2021). An important feature of this species is that it withstands low fertility soils, although it will do better on fertile soils. Hybrids have been formed with *E. pellita* (probably *E. biterreana*) in Indonesia and Brazil, and these have the excellent form of *E. pellita*, with a lower bark percentage, better growth and the high wood density inherited from both species. Apparently no tree improvement program has focused specifically on *E. brassiana* as yet. However, for the Af, Am and Aw climates it is well suited and should be one of the partners

considered for hybridization for Af climate, due to the high wood density and to its adaptation to equatorial conditions. The best provenances for equatorial climates originate in PNG.

Eucalyptus leptophleba

This species is in *Symphyomyrtus*, section *Adnataria*, series *Striolatae* (Nicolle 2019). No literature about this species as a plantation species has been found. Boland et al. (2006) describe its occurrence on Cape York Peninsula, extending into western PNG. It has very dense wood in natural populations. It is a medium sized tree up to 25 m. It does have a good adaptation to hot and humid climates, and probably the PNG provenances, if they can be obtained, would prove best for Af and Am climates. It is worthwhile to be tried in equatorial climates, due to its natural occurrence.

Since it belongs into the section *Adnataria*, it is questionable if it could be used as hybrid partner with species in the sections *Maidenaria*, *Latoangulata* and *Exsertaria*. *E. paniculata*, which also belongs into the section *Adnataria*, is not known to easily produce hybrids with species of the above three sections. However, it must be tried. If *E. leptophleba* proves to be a good plantation species for equatorial climates, breeding programs with it must be started and hybridization trials as well.

Eucalyptus urophylla

This is another of only a handful of extra-Australian eucalypts and it occurs on eight of the Lesser Sunda Islands of Indonesia and East Timor, usually from 500-2000 m asl, precipitation ranging from 600-2500 mm, with a dry season of 4-6 months (Dvorak et al. 2018). Due to the dry season and altitude in its native range, it will probably not be adaptable to Af climates, even though some provenances might prove better adapted than others. It can be used mainly as a hybrid partner, both for the Af and also Am climates, possibly with *E. pellita* or *E. deglupta* participating in the hybridization as a single partner or in 3-way and 4-way crosses. It definitely deserves wide testing for equatorial climates, but it is susceptible to leaf blights in hot and warm environments. Since such areas are different from the higher altitude areas of natural occurrence, the species as a whole may not be adapted. However, breeding and especially hybridization will select and inject the genes from other species to overcome this climate incompatibility. *E. urophylla* is one of the main species for hybridization in the subtropical world; over 80 % of the hybrids in Brazil contain some *E. urophylla* in them (Assis 2015) and it is also used as a pure species. There are several breeding programs with it. It hybridizes easily with many species, also with *E. grandis*, *E. saligna*, and several in the *Exsertaria* and *Maidenaria* section and very frequently results in heterosis when hybrids are produced. Therefore, it must be considered one of the priority species for eucalypt breeding in equatorial climates. The many crosses already using *E. urophylla* enrich the gene pool to be tried closer to the equator.

Other species for hybridization

The exclusively extra-Australian and much smaller species *E. alba* var. *alba*, *E. orophila* and *E. wetarensis* might be tried for hybridization also as they come from hot lowland climates. While *E. orophila* and *E. wetarensis* are very close to *E. urophylla* belonging into the section *Latoangulata* series *Robustae*, *E. alba* var. *alba* belongs into the section *Exsertaria* and could possibly contribute genes for deep roots and quick establishment in areas of low fertility, as presumably *E. brassiana*, *E. tereticornis* var. *tereticornis* and *E. camaldulensis* from *Exsertaria* would. However, the small size of these species relegates them to a secondary level for hybridization.

While *E. grandis* and *E. saligna* are not appropriate for equatorial climates, they do have growth and wood characteristics which make them attractive for hybridization into the species adapted to those climates. Similarly, *E. longirostrata* and *E. punctata* could also add genes of interest.

In the section *Transversaria* there is *E. camaldulensis*. This species has the widest spread of any species over Australia and has been subdivided into seven subspecies by McDonald et al. (2009). Among the north Australian subspecies which are more adapted to hot environments are *E. camaldulensis* ssp. *acuta*, ssp. *obutisa* and ssp. *simulata*. The species has been domesticated widely and there are good seed sources available for trials. It is quite susceptible to the *L. invasa* gall wasp, but with a wide variation of resistance among the subspecies, provenances and individuals. In West Africa, in the subspecies *obutisa* from Katherine River, NT, Australia, only 5 % of the individuals in plantation were attacked. *E. camaldulensis* is remarkable in that it is usually associated to river banks and thus called River Red Gum, and can tolerate several months of flooding (Water for a Healthy Country 2004). Seedlings of *E. camaldulensis* can produce aerenchymatous roots under flooding (Water for a Healthy Country 2004).

Outside Australia this species is generally associated with drought tolerance, and establishes in poor soil by quickly developing a deep tap root. Root development is often not understood. Christina et al. (2011) found that in deep soils *E. grandis* deep root development was 85 % of above soil growth until roots reached the water table. In *E. camaldulensis* it would probably be quicker and deeper. In Ghana *E. camaldulensis* grows continually throughout the 5-6 months of the dry period. While the pure species will most probably not survive or flower in hot and humid environments, as a hybrid partner it may impart the quick establishment, growth and adaptability to poor soils, which probably was the case in the *E. deglupta* x *E. camaldulensis* hybrid K7 in Southeast Asia in the 1990's and 2000's (Ito 2009). Many equatorial regions present heavy waterlogging in part of the year and often have poor, leached soils, for which the genes contributed by *E. camaldulensis* and other species from the *Exsertaria* section could be very helpful in overcoming. The hypoxia which comes with flooding or compacted soils is detrimental to most trees, which switch from respiration to fermentative processes and glycolysis in order to survive (Kreuzwieser et al. 2014, Liu et al. 2015). Compacted, hypoxic soils lead to splitting of the bark and stunted growth with consequent invasion by fungi and bacteria in equatorial climates

(Rosa, A., personal communication, 2020). *E. camaldulensis* and other *Exsertaria* species' genes (e. g. *E. brassiana* and *E. tereticornis* var. *tereticornis*) could help alleviate this problem when introduced into species well adapted to the climate but not to poor, compact or drenched soil conditions. Most eucalypt species demand deep drained soils with at least moderate fertility, but several *Exsertaria* species thrive in poor, compacted, dry or waterlogged soils.

There are many more possibilities available for hybridizing for equatorial climates. Within the section *Maidenaria* are most of the species used for cold hardiness (*E. globulus*, *E. maidenii*, *E. bicostata*, *E. nitens*, *E. dunnii*, *E. viminalis*, *E. macarthurii*, *E. smithii*, *E. benthamii*, *E. badjensis* and more). Several of these carry genes for high quality wood for use in the cellulose industry. Since many of these, when crossed with *E. urophylla* (very tropical) yielded heterotic hybrids with increased wood quality for pulp and adaptability to the tropics, it might be of much interest to also cross them with the highly adapted equatorial species, such as *E. pellita* and *E. deglupta*, in order to obtain adapted hybrids with quality wood for the cellulose industry.

Since much hybridization has already produced very productive hybrids in the subtropical regions, these same hybrids are a good starting point to introduce into the species adapted to the equatorial climate.

Dangers associated with short rotation plantations of Eucalyptus species and hybrids in the equatorial regions

There are dangers associated with short-rotation eucalypt plantations. All of them are susceptible to suddenly appearing or adapting pests and diseases. Many insects may appear suddenly due to accidental introductions. The adaptation of *Ceratocystis manginecans* to *Acacia mangium* detected in Southeast Asia (Tarigan et al. 2011) in this century is threatening all the widely planted *A. mangium* plantations. This disease also attacks the occasional *E. biterranea* tree. It may remain in the soil for many years in the form of aleuroconidia (Nasution 2019). *Ganoderma philippii* similarly is attacking *A. mangium* and the incidence increases in each rotation (Page et al. 2020). These diseases until now have been impossible to control by biological means (Nambiar et al. 2018). The spread of the Australian gall wasp *L. invasa* was first detected in Israel in 2000 and quickly spread all over the world, showing up in Brazil in 2008 (Silva 2019). The very successful hybrid, K7, of *E. camaldulensis* x *E. deglupta* in Thailand, Laos and Vietnam (Ito 2009), later was abandoned due to its susceptibility to *L. invasa*. *Thaumastocoris peregrinus*, *Ophelimus gaskelli*, *Glycapsis brimblecombei* and the *Gonipteris* spp. complex appeared in the last decades in Brazil (Silva 2019) and several continents and countries.

The other threat from short-rotation eucalypt plantations is that they may deplete the soil of vital nutrients if not managed carefully (Harwood 1998, Harwood and Nambiar 2014b), especially during the inter-rotational period. Eucalypts demand soils of moderate to high fertility (Harwood 1998). Since eucalypts do not fix nitrogen as acacias do, additional nutrients have to be supplied externally by supplemental fertilization.

Both problems can be solved. Short rotation plantation trees associated to an active breeding program aiming at constantly producing new hybrids, and the concomitant planting and testing of different clones is a good strategy to stay ahead of susceptibilities and new surges of pests and diseases. Such strategies have been very successful in Brazil and South Africa. Fertility problems can be alleviated by leaving bark and residues of harvesting in the field and by appropriate fertilization schemes. The mixed planting of *A. mangium* and *Eucalyptus* was positive in Congo in an Am climate, leading to more overall above-ground production, but not on an Aw site in Brazil, where water may have been the limiting factor (Epron et al. 2013). In Brazil and South Africa in spite of new pests and diseases appearing, productivity of eucalypt plantations has constantly increased over the last 40 years (Harwood and Nambiar 2014a). In Brazil productivity of 25-30 m³/ha/year last century, is in the range of 35-45 m³/ha/year now, exceeding 60 m³/ha/year occasionally (Rezende et al. 2014) while many new pests appeared. This progress was achieved by changing and diversifying to more productive and resistant hybrids and clones and by continuously optimizing forest management.

Corymbia

Another genus in the eucalypts with planting possibilities in Af climates is *Corymbia*. This genus comprises only two subgenera (*Corymbia* and *Blakella*) and approximately 95 species and several subspecies (Nicolle and Jones, 2018).

According to Nicolle (2019) the classification of the here mentioned taxa is represented in Table 5.

(possibly *C. clarksoniana*), *C. latifolia*, *C. tessellaris*, *C. papuana* and *C. disjuncta*. Hence this genus is also well represented in hot, humid environments (Af and Am). Moreover, in the extreme north and humid North Territory and York Peninsula, potential species for adaptation to Af climate occur, such as *C. intermedia*, *C. bleeseri*, *C. trachyphloia*, *C. nesophila* and *C. clarksoniana*. *Corymbia*, as *Eucalyptus*, offers wide possibilities of hybridization. Differently from *Eucalyptus*, the two *Corymbia* subgenera often produce hybrids when crossed.

Several species within this genus attain sizable growth, as is the case of *C. polycarpa*, *C. clarksoniana*, *C. intermedia*, *C. nesophila*, *C. torelliana*, *C. citriodora*, *C. variegata*, *C. maculata* and *C. henryi* (Boland et al. 2006). Other tropical species attaining about 15m in their natural environments include: *C. tessellaris*, *C. confertiflora*, *C. ptychocarpa*, *C. bleeseri*, *C. erythrophloia*, *C. trachyphloia*, *C. peltata* and *C. leichhardtii*. There is as yet little experience with many of these species in plantation or as hybrid partners. This is an area of extraordinary possibilities and research.

C. torelliana comes from a humid, high rainfall (800-2,500 mm/year) Am climate, with a summer maximum of rain (Boland et al. 2006). The species has a wide adaptation potential, having been successfully planted in areas with up to 40 frosts/year and dry areas with only 400 mm of rain in Australia. It can be rooted from coppice shoots with relative ease (Rezende et al., 2014; Rezende et al. 2014). It has been crossed more often with *C. citriodora*, *C. variegata* and *C. henryi* (Rezende et al. 2014), but also with several other species of the genus (Dickinson et al. 2007). Successful plantation hybrids have been established in many places in Brazil, South Africa, Australia, and more.

Table 5
Classification of some of the most important species in the subgenus *Corymbia*

Genus	Subgenus	Section	Series	Subseries	species
<i>Corymbia</i>	<i>Corymbia</i>	<i>Corymbia</i>	<i>Trachyphloiae</i>		<i>trachyphloia</i>
"	"	"	<i>Dorsiventrals</i>		<i>ptychocarpa</i>
"	"	"	<i>Dorsiventrals</i>		<i>polycarpa</i>
"	"	"	<i>Dorsiventrals</i>		<i>clarksoniana</i>
"	"	"	<i>Dorsiventrals</i>		<i>intermedia</i>
"	"	"	<i>Isobilaterales</i>	<i>Peltiformes</i>	<i>nesophila</i>
"	"	"	<i>Isobilaterales</i>	"	<i>bleeseri</i>
"	"	"	<i>Isobilaterales</i>	<i>Limitaneae</i>	<i>erythrophloia</i>
"	<i>Blakella</i>	<i>Naviculares</i>			<i>peltata</i>
"	"	"			<i>leichhardtii</i>
"	"	<i>Torellianae</i>			<i>torelliana</i>
"	"	<i>Maculatae</i>			<i>citriodora</i>
"	"	"			<i>variegata</i>
"	"	"			<i>maculata</i>
"	"	"			<i>henryi</i>
"	"	<i>Abbreviatae</i>	<i>Tessellatae</i>		<i>tessellaris</i>
"	"	"	"		<i>confertiflora</i>

There is not a single exclusively extra-Australian species, but there are approximately five occurring in Australia and Papua-New Guinea or Indonesia (Nicolle 2019): *C. novoguineensis*

It is remarkable that it is possible to hybridize widely among the two subgenera *Blakella* and *Corymbia* (Dickinson 2007). Most of the possible hybrids, even of the taller species have not been tried yet.

The wide adaptability seems to be general in several *Corymbia* species. Thus, *C. citriodora*, coming from a typical summer rainfall area in Southeast Queensland and Northeast New South Wales, has been successfully established in the winter rainfall area (Mediterranean climate) in Perth, where beautiful mature trees of it line some streets. This adaptation from Cw climate warm temperate with dry winter (Cw) to warm temperate with dry summer (Cs) is an amazing potential, not found in most species in the genus *Eucalyptus*. Thus it is not surprising to find the hybrid *C. torelliana* x *C. citriodora* being established successfully in a wide variety of climates in Brazil, Venezuela, Honduras, West Africa and Australia in Am and Aw climates. There is anecdotal information of some of this hybrid now successfully growing in Kalimantan, Indonesia, Af climate. The ease of cloning *C. torelliana* is passed on to some of the hybrids with *C. citriodora* (Assis 2015). The typical wood density of over 600 kg/m³ makes these widely adaptable species and hybrids attractive for plantations not only for solid wood, energy, pulp (Resende et al. 2014) as well as for their adaptability (Dickinson et al. 2007, Lee et al. 2009, Pegg et al. 2013, Resende et al. 2014, Rezende et al. 2014). The hybrid *C. torelliana* x *C. henryi* grows successfully in South Africa, Brazil and tropical West Africa and is plastic in its adaptation. *C. henryi* originates from north-eastern N. S. Wales and south-eastern Queensland, while *C. torelliana* comes from north-eastern Queensland (Boland et al. 2006).

Among the medium-sized tropical *Corymbia* species there are: *C. tessellaris*, *C. confertiflora*, *C. ptychocarpa*, *C. bleeseri*, *C. erythrophloia*, *C. trachyphloia*, *C. peltata* and *C. leichhardtii* (Boland et al. 2006). Very few of them have been tried in hybridization as yet, but some have been hybridized with *C. torelliana* (Dickinson et al. 2007), both in the subgenus *Corymbia* as in the subgenus *Blakella*, which attests to the wide range of hybridization possibilities.

Of the above species, hybridization is likely to be mainly confined for some time to *C. torelliana* (subgenus *Blakella*, section *Torellianae*) and the spotted gums (subgenus *Blakella*, section *Maculatae*: *C. citriodora*, *C. variegata*, *C. henryi* and *C. maculata*), due to their genetic affinity, the timber value of the species and hybrids, the wide introduction of these species abroad and difficulty to obtain pollen in other countries than Australia. Even in the native habitat in Australia, many years may pass without flowering of some species. Grafting, air-layering and the use of flowering enhancing paclobutrazole helps in countries without natural flowering.

For extreme tropical conditions (Af and Am climates), it will be much advantageous if species attaining high growth, like *C. intermedia* and *C. nesophila* be tried, as species and especially as hybrid partners. Dickinson et al. (2007) obtained best seed set when crossing *C. torelliana* with the closely related *C. citriodora*, *C. variegata* and *C. henryi*, but less when crossed to the also closely related *C. maculata*, all within the subgenus *Blakella*. When crossing *C. torelliana* they obtained reasonable seed set from the crosses with *C. erythrophloia*, *C. intermedia* and *C. clarksoniana*. This shows again the wide hybridization potential within the genus *Corymbia*. The wide crossability allied to heterosis and the plasticity of most hybrids, renders

them very attractive for hybridization and planting in tropical environments.

The species *C. ptychocarpa* – swamp bloodwood from Northwest Australia and North Australia, usually growing in wet sites along river banks (Boland et al. 2006) has large red filaments and has been grown in suitable sites for amenity. It has been hybridized in Australia with *C. ficifolia*, a small red-flowered species from Western Australia and winter rainfall regions and poor adaptation to summer rain areas, producing many clones for ornamental purposes with a wide adaptability in Australia. Several clones of this hybrid are available for sale from garden enterprises. There is obviously an extraordinary adaptability of the hybrids within this genus. *C. ptychocarpa* is not a large species, but planted in small plots in West Africa was successful and had good growth in the first four years.

Queensland and New South Wales developed a breeding program with the pure species of the spotted gums (*C. citriodora*, *C. variegata*, *C. henryi* and *C. maculata*) and hybrids with *C. torelliana*, used as the maternal or seed parent (Lee 2007). Using *C. torelliana* as seed parent assures a much better rooting of clones than when using *C. citriodora*, *C. henryi* and *C. maculata* as seed parent (Assis 2015), as seen in the Table 6. Rooting percentage was double on average, when using *C. torelliana* as seed parent as compared to when using it as pollen donor. Ability to root seems to have a strong maternal component.

Table 6

Rooting percentage of clones from *C. torelliana* as seed parent or *C. citriodora* as seed parent (from Assis, 2015)

Clone	Hybrid	Rooting %
M – 1	<i>C. citriodora</i> x <i>C. torelliana</i>	16.41
M – 4	<i>C. torelliana</i> x <i>C. citriodora</i>	41.91
M – 7	<i>C. torelliana</i> x <i>C. citriodora</i>	43.60
M – 22	<i>C. citriodora</i> x <i>C. torelliana</i>	33.57
M – 43	<i>C. torelliana</i> x <i>C. citriodora</i>	39.34
M – 44	<i>C. citriodora</i> x <i>C. torelliana</i>	13.56

Rooting is further dramatically enhanced, when using shoots originating from the lignotuber region of the trees (Assis 2015), both in seedlings as well as in adult trees, even in pure *C. citriodora* trees, which is considered to be very difficult to root by conventional means as used in *Eucalyptus*. Another technique to obtain higher rooting percentages from shoots is by the use of low-ceiling hermetically closed plastic tunnels to keep mother plants (Assis 2015). The morphology of the leaves in the tunnel changes, becoming a bit lighter and narrow. Techniques such as inducing shoots from lignotuber regions and the use of mini-tunnels improve dramatically the rooting percentage, also in other difficult-to-root eucalypt species. Programs of hybridization such as the above, mainly with *C. torelliana* and the spotted gums are ongoing in Brazil, Australia, Venezuela, Honduras and South Africa and possibly in other parts of the world as well. The plasticity of the hybrids exhibiting heterosis is very promising.

Table 7

Wood densities from some hybrid clones at age 5 and 7 and MAI over bark at age 7 (from Assis, 2015)

Clones	Density at 5 years (kg/m ³)	Density at 7 years (kg/m ³)	MAI (m ³ /ha/yr)
M-01 - <i>C. citriodora</i> x <i>C. torelliana</i>	516	694	47.60
M-03 - <i>C. torelliana</i> x <i>C. citriodora</i>	518	569	42.64
M-04 - <i>C. torelliana</i> x <i>C. citriodora</i>	633	702	24.09
M-07 - <i>C. torelliana</i> x <i>C. citriodora</i>	572	660	49.88
M-22 - <i>C. citriodora</i> x <i>C. torelliana</i>	529	544	41.12
M-43 - <i>C. citriodora</i> x <i>C. torelliana</i>	612	628	42.31

Characteristics such as high wood density, makes these hybrids attractive for solid wood production but also suitable for paper. Table 7 attests to the fact that some hybrids not only result in high wood density (usually higher than 600 kg/m³), but also considerable MAI above bark, as found in Brazil, Rio Doce Valley. Most of the wood properties are inherited in additive manner so that hybrids tend to be intermediate between parents for such characteristics. The interesting fact is also that most hybrids are plastic and perform well in very different environments, displaying low genotype x environment variation.

The hybrids of *C. torelliana* x *C. citriodora* may exhibit a high bark percentage, varying from 8-30 % of the total wood (Assis, personal information 2021), but with a wide variation to select from.

Corymbia species are not immune to diseases, with *Puccinia psidii* (Pegg et al. 2013) and *Quambalaria pitereka* -being two of them, but with some tolerance and even resistance in several hybrids with *C. torelliana* as one of the parent (Lee 2007). Kino pockets often are formed when some species like *C. citriodora* are exposed to physical stress. Kino pockets and veins are detrimental when using the trunks for solid wood or for pulp. Kino seems not to occur in the hybrid with *C. torelliana*. In Rio Doce Valley in Brazil, there is a problem with many eucalypts, also *C. citriodora*, which appears in dry winters, with rolling of leaves and tip drying, from a not yet clearly defined origin and often called "tip-drying or physiological disturbance of Rio Doce Valley". *C. torelliana* does not exhibit this problem and neither does the hybrid with *C. citriodora*.

The pure species spotted gums were strongly attacked by *Quambalaria pitereka* leaf blight in the programs which in the 1990's led to a practical abandonment of these valuable timber species for plantations in Queensland, until tolerant provenances were found, except in *C. henryi*. *C. torelliana* was not *Quambalaria* susceptible and hence was used as a parent for hybridization, being also amenable to vegetative propagation by coppice shoots, as are its hybrids with all the spotted gums (Lee 2007). Frost resistance in the hybrids was similar to the spotted gum species. Many hybrid families displayed heterosis with better height and diameter growth, straightness, *Quambalaria* tolerance, erinose mite tolerance and better coppice rooting ability than the pure species. The families were stable across many sites (Lee 2007).

The above facts show that many hybrid *Corymbia* are very promising for productivity, resistance to diseases, are

amenable to rooting from coppice shoots, plastic in their adaptability to varied environments where they have been tested. However, there are diseases and insects which can attack either parent or hybrids. *C. torelliana* has been attacked by defoliating beetles in some places in Brazil and on Borneo, especially on seedlings. In West Africa, grasshoppers preferentially foraged on *C. citriodora* and *C. torelliana* x *C. citriodora* hybrids, but neglected pure *C. torelliana*.

Most hybridization has taken place using *C. torelliana* as maternal parent, and the spotted gums as paternal parent. The hardly explored hybrid possibility using other species still remains open. For Af climates, the uses of *C. torelliana*, *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* and again the spotted gums as species but especially as hybrid parents offers many possibilities, but also in Am climate. Diseases and insect attacks are to be expected in those hot, humid environments, but the many hybridization potentials seem to be able to overcome these difficulties, as is being shown in Brazil, South Africa and elsewhere in the genus *Eucalyptus*.

Conclusion

High forest productivity can be obtained in the hot, humid, equatorial Af climate zones; high rainfall all year round helps to attain it. By breeding with adapted *Eucalyptus* species and those tolerant of temporary flooded and poor soils such as *E. biteranea*, *E. deglupta*, *E. tereticornis* var. *tereticornis*, *E. brassiana*, and species successful in subtropical areas, such as *E. urophylla*, *E. grandis*, *E. camaldulensis*, Brazil and Indonesia have produced successful hybrid clones. Furthermore, in the genus *Corymbia* the chances stand equally high, if *C. torelliana*, *C. citriodora*, *C. variegata*, *C. henryi* and *C. maculata* and their hybrids are used. In addition, species which should be tried pure and as hybrid partners 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*. Short rotation forestry with many hybrid combinations and vegetative propagation help avoid and evade disease surges by quickly replacing existing clones by new ones and by maintaining plantations with a wide composition of different genotypes in the clones. At the same time, clonal short-rotation

forestry is a challenge for management in order to avoid nutrient depletion of soils, which can be overcome by careful nutrient and fertilization schemes, also by mixing into the plantation nitrogen-fixing species or rotating with these and by leaving foliage and bark in the field at harvest.

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