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An assessment of potential responses of *Melaleuca* genus to global climate change

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Abstract The genus *Melaleuca* consists of around 260 species covering over eight million hectares (including native and introduced species) and distributed mostly in Australia, but also occurring in South-East Asia, the Southern United States and the Caribbean. *Melaleuca* populations predominantly occur in wetland or/and coastal ecosystems where they have been significantly affected by climate change. This paper assesses the potential responses of the *Melaleuca* genus to climate change, based on the synthesis of worldwide published data. The main findings include: (i) that the *Melaleuca* genus has a rich species diversity, and significant phenotypic diversity in a variety of ecosystems; (ii) they demonstrate significant local adaptation to harsh conditions; and (iii) the fossil records and taxon biology indicate the evolution of the *Melaleuca* genus began around 38 million years ago and they have survived several significant climatic alterations, particularly a shift towards cooler and drier climates that has occurred over this period. These findings show that the *Melaleuca* genus is highly resilient and adaptable and based on this, this paper argues that *Melaleuca* can adapt to climate change through Wright's 'migrational adaptation', and can be managed to achieve sustainable benefits.

Keywords Adaptation · Climate · *Melaleuca* · Forest · Population

1 Introduction

Humans and other organisms must find ways to adapt to the effects of global climate change. Vegetation is not only affected by climate change, but also plays an important role in its

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mitigation by the uptake of carbon dioxide (IPCC 2003). Plant communities, and/or populations that can respond quickly to climate change are highly valuable. Healthy vegetation ecosystems that can adapt to climate alterations associated with human activity would play a significant role in mitigating its effects. There are over eight million hectares of wetland or/and coastal plant assemblages dominated by the *Melaleuca* genus on Earth, so it is important to determine how the *Melaleuca* genus responds to climate change, from both ecological and humanistic viewpoints.

Firstly, *Melaleuca* forests are very important ecological systems, especially in the wetlands and/or peatlands of tropical and subtropical regions. In association with other plant species, *Melaleuca* dominated ecosystems can provide an important habitat for fauna, as well as protecting soil, peat and water and providing a significant carbon store. *Melaleuca* forests are very diverse and the species composition depends on the prevailing conditions. In the Australian swamp forests, several *Melaleuca* species are associated with other trees (e.g. *Eucalyptus robusta*, *Lophostemon suaveolens*), sedges (e.g. *Baumea rubiginosa*, *Lepironia articulate, Schoenos breviofolius*, *Dapsilanthus ramosus*, *Gahnia sieberiana*, *Phragmites australis,* and *Ischaemum* spp.), swamp rice grass (*Leersia hexandra*), blady grass (*Imperata cylindrical*), saltwater couch (*Sporobolus virginicus)*, and ferns (e.g. *Stenochlaena palustris* and *Blechnum indicum*) (EPA 2005).

In the Mekong Delta of Vietnam (Buckton et al. 1999; Wetlands of South East Asia n.d.), *Melaleuca cajuputi* is associated with 77 other plant species. In Tulang Bawang of Indonesia, *Melaleuca cajuputi* is found in secondary swamp forests with species such as *Barringtonia acutangula*, *Lagerstroemia speciosa*, *Licuala paludosa, Sapium indicum,* and ferns (Zieren et al. 1999). In southern Thailand, *Melaleuca* trees are found alongside *Melastoma malabathricum,* ferns (e.g. *Blechnum indicum, Stenochlaena palustris,* and *Lygodium microphyllum)* and sedges (e.g. *Lepironia articulata* and *Scleria sumatrana*) (Tomita et al. 2000).

Melaleuca swamp forests are important sites for preserving biodiversity because they hold a remarkable diversity of fauna. About 23 species of mammals, 386 species and subspecies of birds, 35 species of reptiles, six species of amphibians, 260 species of fishes, and about 92 species of waterfowl have been reported in the Mekong Delta of Vietnam. These include large populations of cormorants, herons, egrets, storks and ibises, which nest in huge colonies in the mangroves and *Melaleuca* forests of this region (Buckton et al. 1999; Wetlands of South East Asia n.d.). A wide variety of plants and animals also occur within the *Melaleuca* (Tea-tree/Paperbark) swamp forest of Australia, e.g. with *Melaleuca* trees providing shelter and nesting sites for a range of bird species, fallen timber providing shelter for reptiles and other terrestrial animals, and temporary ponds provide breeding habitat for frogs (*Rheobatrachus spp.*) and other aquatic creatures. Koalas (*Phascolarctos cinereus*), echidnas (*Tachyglossus aculeatus*), and wallabies (e.g. *Wallabia bicolor*, *Petrogale inornata*, *Petrogale penicillata*, and *Petrogale xanthopus celeris*) also occur in these forests (EPA 2005).

Secondly, from a human socio-economic perspective, *Melaleuca* forests can provide timber for building and furniture. Other traditional uses, such as for fuel wood, charcoal, tea-tree oil, and honey are still employed today [e.g. in Indonesia, Malaysia (Saberioon 2009), Thailand (Nuyim 1998), Cambodia (Hiramatsu et al. 2007), and Vietnam (Duong et al. 2005)]. In Australia, *Melaleuca* forests are used for tea-tree oil and honey and their landscape and aesthetic values are recognised as being extremely valuable (DAFF 2008). Many *Melaleuca* species have been selected and incorporated into agroforestry systems (Turnbull 1986). Some *Melaleuca* forests and woodlands in Australia have become cultural and heritage sites [e.g. there are more than 400 Indigenous Cultural Heritage sites in the coastal *Melaleuca* swamp wetlands in Queensland, most dating from the mid Holocene (last 4000 years) (EPA 2005)]. *Melaleuca* forests can also store a large volume of soil organic carbon, especially in the peatlands (e.g. in Indonesia, Malaysia, Thailand, and

Vietnam). The capacity of carbon stores in *Melaleuca* forests is particularly high in Australia, with a total area of over 7.556 million hectares (MPI 2008).

Melaleuca forests are mostly located in wetlands and coastal regions (Blake 1968; DAFF 2008), which makes them vulnerable to climate change as these regions are likely to be the most significantly affected by rising sea levels (Gilman et al. 2008) and/or increased climatic variability, particularly drought (IPCC 2003, 2006). Scientists believe that global climate change threatens species survival and the health of natural systems. In the wetlands, both the quantity and quality of the water supply are vulnerable and wetland habitat responses will be different depending on regional conditions, and research is required to determine the effect of climate change on different habitats (e.g. floodplains, mangroves, seagrasses, saltmarshes, Arctic wetlands, peatlands, freshwater marshes, and forests) (Erwin 2009).

Several studies have been carried out worldwide on the vulnerability of plant species to climate change, and their mitigation and adaptation responses. These include: 66 species studied in Thailand (Trisurat et al. 2011); the impact on the distribution of plant forest species, such as tropical pines in South East Asia (van Zonneveld et al. 2009) and future potential distribution of *Melaleuca quinquenervia* (Watt et al. 2009); the response of a variety of tree species at global scale (Hansen et al. 2001); the adaptation of tropical and subtropical pine plantation forestry (Leibing et al. 2009); the adaptation of species in tropical managed forests (Nkem et al. 2008). Several studies have investigated the responses of *Melaleuca* species to local climatic variability, but no studies have looked at the potential mitigation and adaptation responses of *Melaleuca* forests to climate change. Hence, this paper uses published data from around the world to review the natural mitigation and adaptation responses of the *Melaleuca* genus to climate change (past, contemporary and future), as well as discussing sustainable management practices of *Melaleuca* forest under future global climate change scenarios.

2 Vulnerability of *Melaleuca* forests to global climate change

As discussed above, *Melaleuca* forests mostly occur in coastal regions and wetland areas (e.g. in the coastal regions of the eastern and northern Australia, Papua New Guinea, and New Caledonia, and in the peatlands and lowlands of Indonesia, Malaysia, Thailand, Cambodia, and Vietnam, and as introduced plants in the USA). Besides the threats of human activities to the forests (e.g. landuse change, logging and burning), particularly in Indonesia (Anderson and Bowen 2000), and Malaysia (Wetlands International – Malaysia 2010), *Melaleuca* swamp forests are also threatened by the early consequences of climate change [e.g. sea level rise is increasing flooding in the Mekong River Delta of Vietnam (Erwin 2009)], which was predicted as one of three highest vulnerable coastal regions in the world by IPCC (Nicholls et al. 2007).

Coastal and lowland regions will be the areas most affected by global climate (Nicholls et al. 2007). If the sea level rises, large areas of the *Melaleuca* swamp forests will be affected by salinity, to which they are critically vulnerable. If the United Nations Intergovernmental Panel on Climate Change (IPCC) current scenario of future climate eventuates, the CLIMEX™[1] program suggests that the distribution of *Melaleuca quinquenervia* will change radically, with this species migrating to higher latitudes (Watt et al. 2009). This is one of the widespread species within the genus *Melaleuca*, though many other species may be just as or even more vulnerable to future climate change.

[1] CLIMEX is software introduced by Sutherst et al. (2007) that the dynamic model uses an annual Growth Index (GIA) to describe the potential for population growth as a function of soil moisture and temperature during favorable conditions.

In Australia, the vulnerability index is a comparative measure of vulnerability for local areas of interest within the forestry regions. The government reported that all six regions (Fig. 1) have been assessed as high and very high by this index (Australian Government 2011). They are all coastal regions that are at significantly high risk from climate change, particularly rising sea levels (Australian Government 2009). Of those, R2, R3 and R4 occupy more than 90 % of the total Australian *Melaleuca* forest area. A notable example is Kakadu National Park, which is dominated by *Melaleuca* forests and has been also assessed to be particularly vulnerable to climate change (WBM 2011).

3 Nature of the *Melaleuca* genus and It's potential responses to climate change

3.1 Wide natural distribution of *Melaleuca* forests

In Australia, *Melaleuca* is the third largest plant genus of sclerophyll vegetation, after *Acacia* and *Eucalyptus*, consisting of about 260 species (DAFF 2008). Most of them are endemic species (only occurring within Australia). There are seven species that occur naturally outside Australia, including *Melaleuca cajuputi, Melaleuca dealbata, Melaleuca leucadendra, Melaleuca nervosa, Melaleuca quinquenervia, Melaleuca stenostachya,* and *Melaleuca viridiflora* (Craven 1999). The original natural distribution of *Melaleuca* species is generally considered as including Australasia, Oceania and South East Asia, (Blake 1968; Brown et al. 2001; Craven 1999). The range of their distribution is generally considered to be within

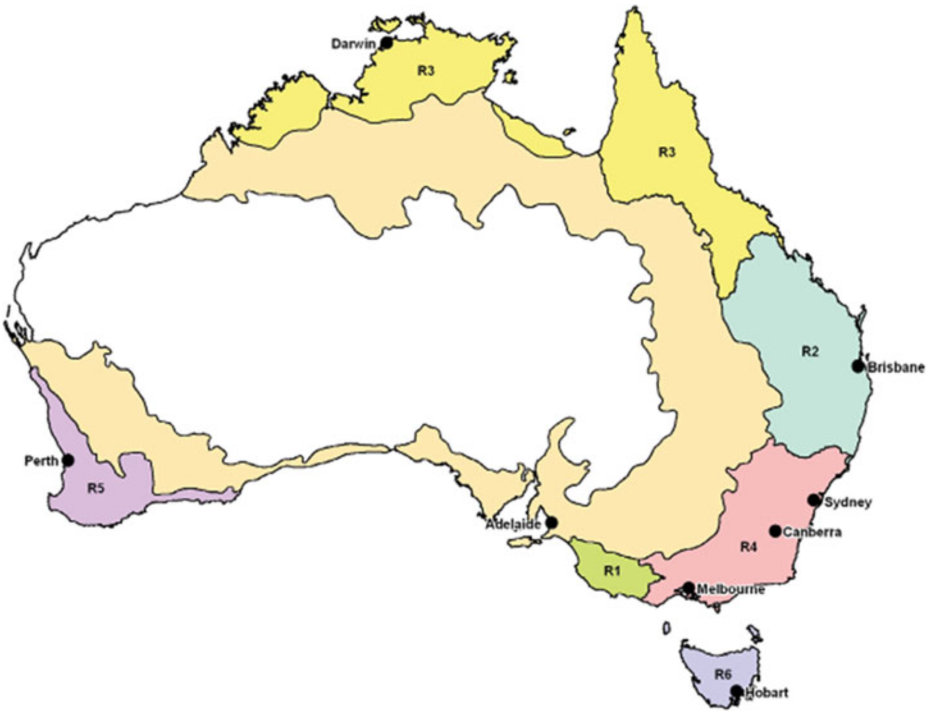

Fig. 1 Six regions of Australia (R1, R2, R3, R4, R5, and R6) where the forests may be significantly affected by climate change. *R* region [Source: Australian Government (2011, p. 1)]

latitude 12°N–18°S and longitude 95°E–158°E, but this information may be out of date. Later studies show that, in Vietnam, *Melaleuca cajuputi* is naturally distributed as scattered shrub populations along the sandy coastal regions in the middle Provinces and up to the Northern low fertility hilly regions of Thai Nguyen and Vinh Phuc Provinces (Cuong et al. 2004) and suggests a more northerly natural occurrence of *Melaleuca* (i.e. to 21°N).

Other studies have reported that *Melaleuca cajuputi* occurs in Cambodia as natural populations in the swamp forests at the rear of Mangrove forests in the coastal regions (UP-MSI et al. 2002; WRM 2006), and is found in Kampong Thom about 300 km inland (Hiramatsu et al. 2007). *Melaleuca cajuputi* also has been recorded to occur naturally in Burma, Myanmar (Weiss 1997), but detailed information is lacking. Along the coastal areas of New Zealand, *Melaleuca howeana* is the dominant species in the coastal scrub vegetation (Mueller-Dombois and Fosberg 1998).

Beyond their natural distribution, the *Melaleuca* genus has invaded other parts of the globe. As shown in Fig. 2, *Melaleuca* occurs as exotic plants that have invaded a wide area in the southern United States and South America. In southern Florida, *Melaleuca quinquenervia* was imported and planted 100 years ago, and has become the worst invasive plant in the wetlands of this region, covering about 202,000 hectares (Turner et al. 1998). *Melaleuca* plants also occur in others states of the USA [e.g. Hawaii, California, and Texas (Dray et al. 2006)], and Caribbean countries [e.g. Bahamas, Brazil, Colombia, Costa Rica, Cuba, Dominican Republic, Guyana, Honduras, Mexico, Nicaragua, Puerto Rico, and Venezuela (Ferriter 2007)]. After a hundred years, *Melaleuca quinquenervia* has become a naturalised species in these regions through seed regeneration, as they do in their native regions.

Result from the CLIMEX™ model has demonstrated that the climate requirements of *Melaleuca quinquenervia* are best met in South-East Asia, the Caribbean, Central and South America, and the Gulf coast in the southern USA (Watt et al. 2009).

Two species, *Melaleuca quinquenervia* and *Melaleuca cajuputi,* have the widest distribution, and they dominate the current *Melaleuca* populations around the globe. Most of the *Melaleuca* genus occurs in wetland and coastal regions, which are some of the most vulnerable locations in the world to future climate change. However, the current distribution also indicates that they have the ability to adapt to a wide range of climates. Under the climate change scenario of IPCC, the CLIMEX™ model indicates there will be a marked

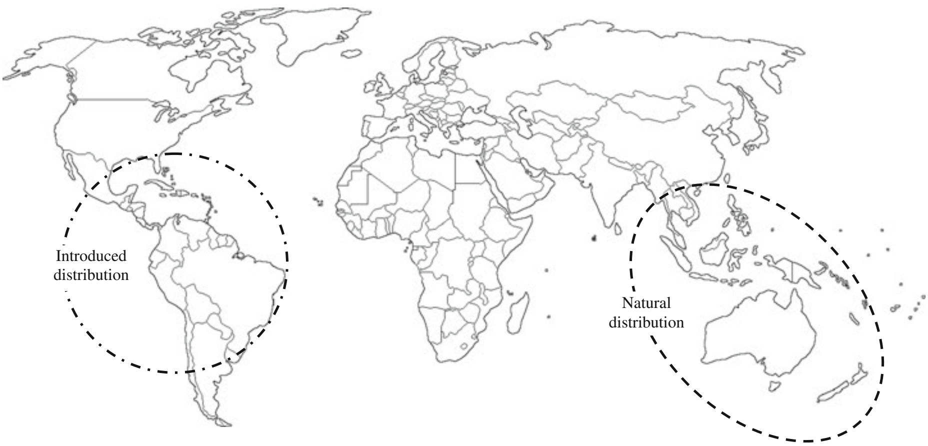

Fig. 2 The most significant locations of current *Melaleuca* populations around the globe (showing both native and introduced locations where these species have become naturalised via seed regeneration)

contraction of suitable habitat in most regions, but they may be able to expand to south-east China, southern Europe, and northern New Zealand (Watt et al. 2009).

3.2 The botanical characteristics of *Melaleuca* and potential responses to climate change

The phenotypic characteristics of plants represent the interaction between the plants and the environment. Some characteristics (e.g. tree form, leaf, flower, seed and bark) can adjust to mitigate, and/or adapt to, changes in the environment, or even react to harsh stresses.

The wide variation in botanical characteristics demonstrates the ability of the *Melaleuca* genus to adapt to the different conditions in a variety of locations. There are 260 species of Melaleuca trees; some are very tall with large trunks (e.g. *Melaleuca argentea, Melaleuca leucadendra,* and *Melaleuca quinquenervia*)*,* some are shrubs (e.g. *Melaleuca arcana, Melaleuca bracteata*, and *Melaleuca symphyocarpa*), some are small trees (e.g. *Melaleuca dealbata*, *Melaleuca ericifolia, Melaleuca nervosa*, and *Melaleuca viridiflora*), and some have different forms in different conditions (e.g. *Melaleuca cajuputi*). In Vietnam, *Melaleuca cajuputi* occurs naturally in different forms: as shrubs in the sandy and/or unfertile lands in the middle and north of this country, and as a small to big tree in the lowlands of south Vietnam (Cuong et al. 2004). In the Northern Territory, *Melaleuca cajuputi* occurs as very large and tall trees (up to 40 m in height, and 1.2 m diameter) (Blake 1968; Doran and Turnbull 1997).

Melaleuca leaves are also diverse, but are generally smaller than many other tropical plant species. Some are thick (e.g. *Melaleuca bracteata* and *Melaleuca viridiflora),* some are hairy (e.g. *Melaleuca cajuputi* and *Melaleuca dealbata*), and some are needle-like (e.g. *Melaleuca ericifolia)* (AgroForestry Tree Database n.d.; Australian Tropical Rainforest Plants 2010; Blake 1968; Doran and Turnbull 1997; Turnbull 1986; Victorian Resources Online 2011)*,* which shows the potential adaptations of *Melaleuca* foliage to various environmental conditions.

All species of the *Melaleuca* genus possess thick and layered bark. Many of them have papery layered bark (e.g. *Melaleuca arcana, Melaleuca cajuputi, Melaleuca dealbata*, *Melaleuca leucadendra, Melaleuca nervosa*, *Melaleuca quinquenervia*, and *Melaleuca viridiflora*), and some have hard and/or peeling bark (e.g. *Melaleuca bracteata*, *Melaleuca ericifolia,* and *Melaleuca symphyocarpa*) (AgroForestry Tree Database n.d.; Australian Tropical Rainforest Plants 2010; Blake 1968; Doran and Turnbull 1997; Turnbull 1986; Victorian Resources Online 2011). These types of bark confer a remarkable ability to adapt to fire. As global climate progresses, fire may be one of the increasing hazards. Many *Melaleuca* species can resist fire and details are presented in a later section.

Many species of *Melaleuca* genus have a suckering habit (e.g. *Melaleuca bracteata, Melaleuca cajuputi*, *Melaleuca leucadendra,* and *Melaleuca quinquenervia*) (AgroForestry Tree Database n.d.; Australian Tropical Rainforest Plants 2010; Blake 1968; Doran and Turnbull 1997; Turnbull 1986; Victorian Resources Online 2011), which gives them the ability to resist waterlogging in their communities. Wetlands have been considered as one of the habitats that will be most affected by climate change (IPCC 2003, 2006), but *Melaleuca* species are well adapted to flooding conditions.

Flowering seasons are predicted to be affected by climate change because many plants require particular conditions to begin blooming. However, many *Melaleuca* species demonstrate flexibility in their flowering time. In Australian conditions, the flowering seasons of *Melaleuca* species vary: some flower from spring to summer (e.g. *Melaleuca arcana*, *Melaleuca bracteata*, and *Melaleuca ericifolia*), others from autumn to winter (e.g. *Melaleuca argentea*, *Melaleuca nervosa*, and *Melaleuca leucadendra*), and some flower throughout the year (e.g. *Melaleuca cajuputi*, *Melaleuca dealbata*, *Melaleuca nervosa*, *Melaleuca quinquenervia*, and *Melaleuca viridiflora*) (AgroForestry Tree Database n.d.; Australian Tropical Rainforest Plants 2010; Blake 1968; Doran and Turnbull 1997; Turnbull 1986; Victorian Resources Online 2011). In addition, some species can reproduce very early [e.g. *Melaleuca quinquenervia* flowers in 3–4 years in Australian conditions (Doran and Turnbull 1997) and 1–2 years in Florida (Franks et al. 2008); *Melaleuca leucadendra, Melaleuca quinquenervia* and *Melaleuca viridiflora* planted in Vietnam also flower throughout the year, with peaks occurring twice a year (Hoang 2010)]. Thus, it is possible to predict that these species have the ability to adapt their time of flowering in response to climate change.

Fruits and seeds of *Melaleuca* species have particular characteristics to keep the species alive for future generations. Many species produce large numbers of fruits and huge numbers of tiny seeds [e.g. a single mature *Melaleuca quinquenervia* tree that is 10 m in height in Florida may hold 20 million seeds (Hofstetter 1991)]. Generally, the seeds of all species comprise very small capsules. In Australia, the species with largest seed (*Melaleuca argentea)* comprises 788,000 capsules kg^{-1}, and the smallest (*Melaleuca bracteata*) comprises 10,500,000 capsules kg^{-1} (AgroForestry Tree Database n.d.; Australian Tropical Rainforest Plants 2010; Blake 1968; Doran and Turnbull 1997; Turnbull 1986; Victorian Resources Online 2011). In Florida, the seed of *Melaleuca quinquenervia* is much smaller than in Australia, and can comprise 34,000,000 capsules kg^{-1} and its seeds appear to be well adapted to wet/dry conditions (Turner et al. 1998). Seed of *Melaleuca cajuputi* in Vietnam has 36,185,611 capsules kg^{-1}; planted *Melaleuca leucadendra* ranges from 22,251,544 to 20,874,523 capsules kg^{-1}; and planted *Melaleuca viridiflora* has 20,323,300 capsules kg^{-1} (Hoang 2010). The huge number of seeds produced by these *Melaleuca* species gives them a remarkable potential to regenerate. Besides seeds, some species can regenerate by shoot or clone-regeneration [e.g. *Melaleuca ericifolia* in Australia (Robinson 2007; Salter et al. 2010a), *Melaleuca cajuputi* in the barren sandy regions of southern Thailand (Tanaka et al. 2001) and *Melaleuca cajuputi* communities in the unfertile regions of northern Vietnam (personal record)].

Additionally, seedlings of *Melaleuca quinquenervia* that regenerated from seeds were very dense, with 500–2,250 individuals per m^2 (Franks et al. 2006), and the density of mature stands in Florida was between 8,000–132,000 trees per hectare (Rayachhetry et al. 2001).

All the above aspects demonstrate the strong ability for *Melaleuca* species to be highly resilient in the face of climate change.

3.3 The resistance of *Melaleuca* species to harsh conditions and their capacity to respond to climate change

Research has shown that *Melaleuca* species can tolerate various types of extreme conditions (e.g. flood, drought, slight saline conditions, high aluminium concentrations, fire, and other conditions). These harsh conditions currently occur in many locations around the world, and are predicted to increase in future scenarios of global climate change and many *Melaleuca* species can respond to increases in these extreme circumstances.

3.3.1 Resistance to flood and drought conditions

Resistance to floods and drought is key characteristic of many species in the *Melaleuca* genus. Most *Melaleuca* communities occur naturally in wetlands and/or in dry lands. Some are very resilient in wet conditions (e.g. *Melaleuca acacioides, Melaleuca alternifolia, Melaleuca argentea, Melaleuca ericifolia, Melaleuca leucadendra, Melaleuca quinquenervia, Melaleuca saligna,* and *Melaleuca viridiflora*) and can tolerate deep floodwaters that are up to 3 m deep from several months to a year (Blake 1968; Doran and Gunn 1994). Some species survive very well in both deep floodwater and dry conditions [e.g. *Melaleuca cajuputi* communities in Thailand (Suzuki 1999; Tanaka et al. 2001) and Vietnam (Cuong et al. 2004)]. Some species thrive in dry land situations [e.g. *Melaleuca lanceolata (moonah), Melaleuca halmaturorum ssp. halmaturorum, Melaleuca brevifolia,* and *Melaleuca lanceolata ssp. Lanceolata* (Barlow and Cowley 1988; Blake 1968; Cowley et al. 1990; DAFF 2008)].

It is important to determine the survival of seedlings in such conditions. Table 1 summarizes the major studies on flood resistance in *Melaleuca* trees. Testing in pots using *Melaleuca alternifolia*, *Melaleuca cajuputi*, *Melaleuca ericifolia* seedlings revealed various results. Generally, older seedlings can survive much better than the younger ones, and seedlings can survive shorter floods better than longer ones [e.g. 17 % of 2–3 month old *Melaleuca cajuputi* seedlings can still be alive after 2 months (Tanaka et al. 2011); 100 % of 12 month old *Melaleuca alternifolia* seedlings can be alive 100 % after 6 months (Jing et al. 2009)]. On the other hand, in natural conditions in Thailand, *Melaleuca cajuputi* seedlings can remain alive, and still grow, during floods 30 to 50 cm in depth lasting 9 months (Yamanoshita et al. 2001). This suggests that in nature plants can adapt to unstable conditions than in experimental conditions and this is a key characteristic of some *Melaleuca* species to mitigate and adapt to climate change.

3.3.2 Resistance to salinity

Rising sea levels caused by global climate change (IPCC 2003, 2006) will affect large areas of lowlands in coastal regions, thus threatening resident *Melaleuca* populations. Saline-tolerant species of plants, such as Mangroves, are less vulnerable. Unfortunately, many *Melaleuca* species are adapted to freshwater habitats, so they will be significantly threatened. However, some studies have shown that several species can tolerate slight increases in salinity (Table 2). Some *Melaleuca* species occur in slightly saline soil or water conditions [e.g. *Melaleuca acacioides*, *Melaleuca bracteata, Melaleuca ericifolia,* and *Melaleuca hamaturomum* (Blake 1968; Doran and Gunn 1994; Ladiges and Foord 1981; Mensforth and Walker 1996; Salter et al. 2006)], but these are mature communities. Some studies have been undertaken to investigate the ability of *Melaleuca* seedlings to tolerate saline

Table 1 Summary of flood resistance of certain *Melaleuca* species

Species	Seedlings				Study sites	Literature
	Age (months)	*Flooded (months)*	*Depth (cm)*	*Survival (%)*		
Melaleuca alternifolia Cheel.	12	6	20	100	South China (in pots)	(Jing et al. 2009)
Melaleuca cajuputi Powell.	Natural	9	30–50	Growing	Narathiwat, Thailand (at fields)	(Yamanoshita et al. 2001)
Melaleuca cajuputi Powell.	2–3	2	Sub-mergence	17	Narathiwat, Thailand (in pots)	(Tanaka et al. 2011)
Melaleuca ericifolia Smith.	6	9	Up to 44	2	Victoria, Australia (in pots)	(Raulings et al. 2007)

Table 2 Summary of salinity resistance of certain *Melaleuca* species

Species	Seedlings			Study sites	Literature
	Age	*Salinity*	*Survival*		
Melaleuca cajuputi Powell.	2 months	50 mM	3 months	In pots	(Nguyen et al. 2009)
Melaleuca ericifolia Smith.	From seeds	At 14‰	Growth inhibited	In pots	(Ladiges and Foord 1981)
	From seeds	to 21‰	48 days	In pots	
Melaleuca ericifolia Smith.	5 months	2 dS m^{-1}	100 %	In pots—10 weeks	(Salter et al. 2006)
	5 months	49 dS m^{-1}	100 %	In pots—10 weeks	
	5 months	60 dS m^{-1}	90 %	In pots—10 weeks	
Melaleuca ericifolia Smith.	Natural	2.5–5.4 dS m^{-1}	42–100 %	Dowd Morass State Game Reserve, Southeast Australia	(Salter et al. 2010b)
Melaleuca hamaturomum Miq.	21 days	64 dS m^{-1}	15 months	South Australia (in pots and fields)	(Mensforth and Walker 1996)

conditions. Most of these experiments were undertaken in pots (in a greenhouse), and results show that 2 month old *Melaleuca cajuputi* seedlings can survive 3 months in 50 mM of salinity, with a tolerance level calculated from 40.3 to 57.5 % (Nguyen et al. 2009). Furthermore, 90 % of 5 month old *Melaleuca ericifolia* seedlings can survive in 60 dS m^{-1} salinity (Salter et al. 2006). Even more successful than the above two species was 21 day old *Melaleuca hamaturomum* seedlings, which can remain alive for 15 months in 64 dS m^{-1} salinity (Mensforth and Walker 1996). Another field study in the Dowd Morass State Game Reserve, in south-eastern Australia has shown that 42–100 % of wild *Melaleuca ericifolia* seedlings can survive salinities ranging from 2.5 to 5.4 dS m^{-1}, and in these conditions plants can grow from 4.6 m to 5.5 m over 3 years (Salter et al. 2010b).

3.3.3 Resistance to aluminium

In natural settings, several *Melaleuca* species occur in conditions with very high acidity, and aluminium concentrations [e.g. in Mekong Delta of Vietnam (Nguyen et al. 2009)]. Table 3 presents several results showing the remarkable resistance of some *Melaleuca* species to high aluminium concentrations. *Melaleuca bracteata* has been assessed as having high tolerance to aluminium in soils, but *Melaleuca cajuputi* is even more tolerant (Tahara et

Table 3 Summary of the aluminium resistance of certain *Melaleuca* species

Species	Seedlings				Study sites	Literature
	Age	*Aluminium*	*Root tip uptake*	*Tolerance*		
Melaleuca bracteata F. Muell.	2–4 months	1 mM $AlCl_3$	Less Al tightly bound to root tips	High	Narathiwat, Thailand (in pots)	(Tahara et al. 2008a)
Melaleuca cajuputi Powell.	2–4 months	1 mM $AlCl_3$	Less Al tightly bound to root tips	Higher than *M. bracteata*	Narathiwat, Thailand (in pots)	(Tahara et al. 2008a, b)
Melaleuca cajuputi Powell.	2 months	10 mM $AlCl_3$	–	From 63.6 to 76.4 %	In pots within 3 months	(Nguyen et al. 2009)

al. 2008a, b). From 63.6 to 76.4 % of two month old seedlings of *Melaleuca cajuputi* tolerated conditions of 10 mM $AlCl_3$ (Nguyen et al. 2009). However, if exposed to both high aluminium and salinity concentrations, this species demonstrates much lower tolerance (Nguyen et al. 2009).

3.3.4 Resistance to fire and other factors

Besides the ability to tolerate the harsh conditions described above, *Melaleuca* species can also tolerate fire and post mining conditions.

Species that can tolerate fire include *Melaleuca cajuputi* (Tomita et al. 2000), *Melaleuca quinquenervia* (Martin et al. 2010; Turner et al. 1998), and *Melaleuca viridiflora* (Crowley et al. 2009). In southern Thailand, *Melaleuca cajuputi* seedlings regenerate strongly after fire, producing up to 73.8 individuals per m^2, up to 179.8 cm high, and covering 1–4 % of the land area after 3 years (Tomita et al. 2000).

In northern Australia, five major species (*Melaleuca argentea, Melaleuca cajuputi, Melaleuca dealbata*, *Melaleuca viridiflora* and *Melaleuca leucadendra*) share areas where the forests are disturbed by fire and/or floodwater that would otherwise be suitable for rainforest growth (Franklin et al. 2007). In Cape York Peninsula, after impacts from storms and burning over a 3 year period, *Melaleuca viridiflora* recolonised woodland areas within 20 years (Crowley et al. 2009).

In peatlands environments, where there is high potential for fire, *Melaleuca cajuputi* is a main pioneer species. The species germinates, survives and grows well under flood conditions, and its seeds do not lose their germination capacity even after heating to 100°C for 1 hour, which enables *Melaleuca cajuputi* to grow and develop in fire-ravaged peat swamps (Government of Indonesia 2009).

Additionally, *Melaleuca* species can also be resistant to rust caused by *Puccinia psidii* [e.g. *Melaleuca ericifolia* has 100 % resistance (Zauza et al. 2010)].

In Quang Ninh Province—an area of post mining coal in Vietnam, the *Melaleuca* hybrid variety named L19L4 had high survival rate (95.3 %) after 1 year, which is better than *Pinus merkusii, P. massoniana*, natural hybrids of *Acacia* and *Melaleuca leucadendra* (with survival rates of 2.33 %, 15.3 %, 11.3 % and 7.3 %, respectively). Under such post mining conditions, the *Melaleuca* hybrid retained its high survival rate (70–95 %) at 20 months of age, with growth ranging from 1.59 to 2.04 m (Hoang and Tran 2011). Thus, several *Melaleuca* species may be suitable to re-vegetation projects in post mining areas.

3.4 Historical evidence of *Melaleuca* evolution and genotype and potential responses to climate change

Fossil evidence found in Melaleuca Inlet, south-western Tasmania (Jordan et al. 1991), Coal Head, western Tasmania (Rowell et al. 2001), and Cape Van Diemen on Melville Island, Northern Territory (Pole and Bowman 1996) has confirmed that members of *Melaleuca* genus have been present in Australia for at least the last 38 million years. In Tasmania, fossil evidence has shown that the current vegetation in the lowlands of western and northern Tasmania is similar to the fossil vegetation (Rowell et al. 2001). In addition, *Melaleuca* communities still occur naturally around the fossil site at Melville Island (Pole and Bowman 1996). This evidence shows the remarkable ability of the *Melaleuca* genus to adapt to climate change.

As illustrated in Fig. 3, sclerophyll vegetation, including Proteaceae (*Grevillea*, *Banksia* and *Hakea*), *Melaleuca*, *Acacia*, Boronias, and the eucalypts, that there has been a

Estimated time line (years ago)	Characteristics of the climate and geography in Australia	Dominant vegetation
	The Holocene, at about 9,000 BP, the temperatures were higher than at the present in Australia, and there was increased rainfall. The highest sea levels reached in the Holocene was from about 7,500 to 6,000 BP. Since then, the sea levels have been approximately stable [(Monroe 2011) cited from (White 2000)].	Similar present Sclerophyll
10 000		
	Following this wet period, aridity spread towards the margins of the continent, the spread of aridity peaking at the last glacial maximum.	
26 000 38 000	Melaleuca fossils age 26,000–38,000 years old were discovered in Tasmania and Melville islands, NT (Pole & Bowman 1996, Rowell et al. 2001), and in north-eastern Australia and South-East Asia (a major stepwise change) (Kershaw et al. 2003).	
50 000	Between about 55,000 and 35,000 BP, a wet phase, which was less widespread, has been associated with high sea levels and activity of Palaeo channels in south-eastern Australia [(Monroe 2011) cited from (White 2000)].	Sclerophyll and rainforest conifers
63 000	In the Eyre Basin, dunes began to form about 95,000 BP during the last interglacial. Dunes began to form on the areas bordering streams and lakes of the Riverine Plain; that is about half way between the center and the coast, from about 70,000 to 50,000 BP.	
79 000	Dunes began forming in the Lake George Basin, close to the coast, and the Shoalhaven Basin, on the coast, during the last glacial maximum about 20,000 BP.	
86 000	At this time, the peak of the last glacial, it has been estimated that Australia received half the present rainfall and the winds were double their present strength, up to 80% of the continent being covered by wind-blown sand.	Rainforest flowering plants
	The dune fields reached their present state. Also at this time much of the Murray Basin was a salt-sand desert (White 2000)	
116 000	White (2000) described that about 110,000 years ago fluvial activity was the peak, world temperature and sea level maxima by the state of 5,000–10,000 years BP. Around 130,000 years BP, one of two major stepwise changes occurred that increased in sclerophyll vegetation, especially *Eucalyptus* and *Melaleuca* (Kershaw et al. 2003).	

☐ *Rainforest flowering plants* ⁙ *Rainforest conifers* ▨ *Sclerophyll vegetation*

Fig. 3 Schematic of the estimated states of rainforest conifers, rainforest flowering plants, and sclerophyll vegetation over last 130,000 years, along with significant characteristics of the climate and geography in Australia. *BP* before present [Source: adapt from ECOS (1980, p. 7)]

significant increase in these sclerophyll taxa over the last 130,000 years (ECOS 1980; Kershaw et al. 2003). Over time, this vegetation developed to share the Australian continent with rainforest conifers from 79,000 to 38,000 years BP due to the increasing rainfall, and sclerophyll became the dominant vegetation from 38,000 to 10,000 years BP. Today, sclerophyll vegetation still occurs, but the dominant position has been replaced by other plants (ECOS 1980). Present conditions are roughly comparable with those 86 000–79 000 years ago, and with those more than 116 000 years ago (ECOS 1980, p.7). Furthermore, latter study on pollen fossil record in north-eastern Australia and South-East Asia has suggested that sclerophyll vegetation relevantly occurred in the last 250,000 years. The result also demonstrated the environmental conditions over variety of periods (Kershaw et al. 2003; Moss and Kershaw 2007).

Over the past 250,000 years (Kershaw et al. 2003; Moss and Kershaw 2007), due to the changes of climate and geography in Australia, the *Melaleuca* genus has undergone a remarkable evolution to comprise 260 species at present. These species are currently adapted to the varied conditions of Australia and other regions, even surviving in extreme situations. Not only are there morphological differences, but molecular studies have shown that there are the complex relations and evolution of *Melaleuca* species [e.g. molecular phylogeny and biography of *Melaleuca* species (Brown et al. 2001), genetic congruence with *Melaleuca uncinata* complex (Broadhurst et al. 2004), reticulate evolution of *Melaleuca quinquenervia* (Cook et al. 2008), and cpDNA sequences of *Melaleuca leucadendra* complex (Edwards et al. 2010)].

Published studies show that *Melaleuca* species have evolved rapidly since around 30,000 years BP (Before Present). Starting at one species at around 40,000 years BP, today there are about 27 species in the *Melaleuca leucadendra* complex. These details how the *Melaleuca* genus has evolved very rapidly over a relative short time period and is clearly presented in the 'Chronogram showing relationships and estimated divergence times in the *Melaleuca leucadendra* complex, the rest of *Melaleuca* and Myrtaceae, in part' (Cook et al. 2008, p.513). The literature also shows that species of the *Melaleuca genus* have a very close genetic relationship, but they are not monophyletic, which is demonstrated by Brown et al. (2001) and Edwards et al. (2010). We believe that the unique changing conditions of the Australian landscape over the last 130,000 years have provided an environment, which accelerates *Melaleuca* evolution. There is strong evidence to infer that the wide variation of phenotypes in the *Melaleuca* genus helps it to adapt to significant environmental differences and dramatic alterations in climate. Therefore, it is assumed that species of the *Melaleuca* genus will have the ability to adapt quickly to current and future climate alterations, as well as making this genus highly adaptable to new environments (i.e. introduction in southern United States and the Caribbean).

The long history of the *Melaleuca* genus, along with its high genetic adaptability, means that this genera has survived a number of significant environmental alterations and catastrophes (Pole and Bowman 1996; Rowell et al. 2001), particularly over the last 250,000 years (Kershaw et al. 2003; Moss and Kershaw 2007), when there were significant changes in sea-levels (+2 to −120 m) and a dramatic increase in burning. So, we strongly agree with the argument put forward by Kuparinen et al. (2010) that increasing mortality can promote evolutionary adaptation of forest trees to climate change.

4 Discussion on adaptation of *Melaleuca* population and management for carbon storage

A detailed critical review (Breed et al. 2011) that discusses the climate change adaptation responses of trees in the landscape is very relevant to this study. It considers three factors: (i) 'migrational adaptation', which describes the process by which standing genetic variation is redistributed by gene flow and selection among populations (Breed et al. 2011 - acknowledged from Wright, 1932); (ii) 'novel-variant adaptation', which describes the process of increasing frequency, and possibly fixation of, new, beneficial genetic variants that are generated by mutation, recombination or other genetic processes (Breed et al. 2011 - acknowledged from Wright, 1932); and (iii) 'plasticity adaptation', which refers to adaptive plastic responses of organisms to environmental stresses. Additionally, landscape management actions were also considered to contribute to the process of evolutionary adaptation; that is, as human-mediated adaptation (Breed et al. 2011, p.638).

Some *Melaleuca* species may adapt to increased inundation, while others might be killed. Therefore, further research into flexible *Melaleuca* species and populations is needed to develop greater understanding of their adaptive capacity so that the swamp forests can be managed to obtain sustainable benefits.

Enhancing the protection of *Melaleuca* forests is important, particularly in coastal regions, to generate food, medicines, fuel wood, and other products for local human communities and to integrate the introduction of new technologies with traditional uses. Studying and creating agroforestry systems based on *Melaleuca* forests (e.g. rice with *Melaleuca* forest; honey bee feeding with *Melaleuca* forest management; aquaculture combined with *Melaleuca* forests; and mixed planting oil palm and *Melaleuca* by bands or plots) that can adapt to more extensive and longer duration flood conditions, and provide livelihoods in such an environment, will be highly beneficial. Additionally, it is vital to enhance fire management and prohibit human activities that cause fire or degrade the land (e.g. fire used to exploit natural honey, or adding salt water into the canals to control fire in Mekong Delta of Vietnam).

Over 2.1 million hectares of *Melaleuca* forests in Australia are in the conservation areas (e.g. National Parks, Cultural and Heritage zones) (MPI 2008). These conservation areas are valuable not only as ecological systems, but also derive economic value from carbon offsets. A personal estimate is that the financial value of preserving these forests is in excess of US $15 billion (given the Australian Commonwealth Government's price on carbon of US$23/ tCO_2e to be introduced from 1st July 2012). The climate policy in Australia can encourage the development of carbon offset project that might involve *Melaleuca* forests. Additionally, UNFCCC policy is also appropriate to Melaleuca forests in South East Asian countries (e.g. Indonesia, Malaysia, and Vietnam) where REDD+ is legally allocated. However, the carbon sequestration of over 8 million hectares of *Melaleuca* plants should be assessed accurately to determine the available carbon offsets.

Although the introduced species (*Melaleuca quinquenervia*) rapidly invades other native plant communities in the wetlands of Florida and has become an exotic weed, it is considered as an important species for honey bee production (Dray et al. 2006). Although there is a need to prevent the further invasion of this species, the current extent of *Melaleuca* forest in Florida should be managed to produce carbon offsets from the current area of 202,000 hectares.

5 Conclusions

The *Melaleuca* genus can respond quickly to climate change for several major reasons, including: (i) having a rich species diversity (260 species), and a dramatic phenotypic diversity in a variety of ecosystems; (ii) the ability to resist various harsh environmental conditions, such as flooding, drought salinity, high aluminium concentration, and burning; (iii) the fossil records and taxon biology indicate the rapid evolution of the *Melaleuca* genus over the past 38 million years. This evidence emphasizes how well these species and populations can potentially adapt to global climate change, which provides the potential for the development of a sound management strategy for *Melaleuca* species and their populations that can significantly contribute to climate change mitigation strategies through the storage of a large volume of carbon.

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