Forest Ecology and Management 375 (2016) 230–237

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Melaleuca forests in Australia have globally significant carbon stocks

Da B. Tran [a,*], Paul Dargusch [b]

[a] The Vietnam National University of Forestry, Hanoi, Viet Nam
[b] School of Geography, Planning and Environmental Management, The University of Queensland Australia, Brisbane, QLD 4072, Australia

ARTICLE INFO

Article history:
Received 3 February 2016
Received in revised form 17 May 2016
Accepted 20 May 2016
Available online 4 June 2016

Keywords:
Carbon
Conservation
Ecosystem
Inundation
Wetland
Wildfire

ABSTRACT

Melaleuca forest is one of the unique ecosystems in Australia which plays an important role to provide carbon storage helping mitigation to the global climate change, thus understanding how much carbon can be stored in the types of forests is necessary. In this study, data was collected and analyzed from four typical sorts of *Melaleuca* forests in Australia including: primary *Melaleuca* forests subject to continuous water inundation; primary *Melaleuca* forests not inundated by water; degraded *Melaleuca* forests subject to continuous water inundation; and regenerating *Melaleuca* forests subject to continuous water inundation. The carbon stocks of these typical *Melaleuca* forests were 381; 278; 210; and 241 t ha^{-1} of carbon, respectively. Averagely, carbon stocks were 169 (±26) t ha^{-1} of carbon in the above-ground biomass and 104 (±16) t ha^{-1} of carbon in soil and roots. The results provide important information for the future sustainable management of *Melaleuca* forests at both the national and regional scales, particularly in regards to forest carbon conservation and carbon farming initiatives. The results establish that *Melaleuca* forests in Australia hold globally significant stores of carbon which are likely to be much higher than previously estimated and used in national emissions reporting.

1. Introduction

In Australia, about 6.3 million ha of *Melaleuca* forests and woodlands were recorded in 2013 (MIG, 2013). *Melaleuca* ecosystems are mostly occurring as wetland forests, predominantly in the coastal regions of Queensland and the Northern Territory. These forests provide society with multiple ecological and cultural benefits [e.g. biodiversity, habitat, heritage areas (Mitra et al., 2005; DAFF, 2010)]. They both serve as substantial storage and substantial sources of carbon emissions, and as such play an important role global climate change (Tran et al., 2013b), in a similar way to other types of wetland ecosystems around the world (Bernal, 2008; Bernal and Mitsch, 2008; Mitsch et al., 2012), and specifically tropical wetlands (Mitsch et al., 2008, 2010), and temperate freshwater wetlands (Bernal and Mitsch, 2012).

In regards to freshwater forested ecosystems, there are few types of these forests occured on the earth such as cypres, wet pine flats, white cedar forest, wet bottomland hardwoods, blackriver bottom forest, gum-cypress swamps, and swamp *Melaleuca* forest; however their environmental conditions are naturally different, and also vary under types of disturbances. *Melaleuca* forests are unlike most other forest types for which carbon stocks have been assessed.

In addition, data from the Australian Greenhouse Office (AGO) showed that the total carbon store in *Melaleuca* forests and woodlands in Australia in 2008 was 210 Mt C; distributed in about 27.8 t C ha^{-1} (MIG, 2008, p. 117). However, it is argued that *Melaleuca* forests have a much higher potential for carbon storage than these AGO estimates (Tran et al., 2013a), because of the lack of field studies conducted directly on *Melaleuca* ecosystems when the AGO addressed the estimation. Better information is needed on the extent and dynamics of carbon stocks in *Melaleuca* forests, particularly in regards to how these stocks vary between sites exhibiting different levels of disturbance and different hydrological features. Like other wetland ecosystem, *Melaleuca* swamp forests are vulnerable to the impacts of climate change, and these impacts are also likely to change the forest type's carbon stocks. Developing a better understanding of the carbon stocks of *Melaleuca* forests and the factors affecting them, will help improve climate change response strategies. Comprehensive studies covering all forest types and associated site conditions are needed, but these require long time periods and considerable resources. To begin the process, this paper presents the findings of a detailed analysis of the carbon stocks of *Melaleuca* forest areas in Queensland, Australia.

* Corresponding author at: The Vietnam National University of Forestry, Xuan Mai Town, Chuong My District, Hanoi, Viet Nam.
E-mail addresses: tranbinhda@gmail.com (D.B. Tran), p.dargusch@uq.edu.au (P. Dargusch).

http://dx.doi.org/10.1016/j.foreco.2016.05.028
0378-1127/

2. Study sites and methods

Two study sites were selected on the basis that they: (1) were generally representative of *Melaleuca* forests in Southern Queensland; (2) contained *Melaleuca* forest areas exhibiting different levels of disturbance and different types of water inundation; and (3) were accessible within the logistical constraints of the study. The study investigated two sites in South-East Queensland, Australia: Buckley's Hole Conservation Park and Hays Inlet Conservation Park (Fig. 1). A total of 18 major plots were randomly located for carbon assessment covering the following types of *Melaleuca* stands: primary (undisturbed) *Melaleuca* forests subject to continuous water inundation (coded A1); primary (undisturbed) *Melaleuca* forests not inundated by water (coded A2); degraded *Melaleuca* forests subject to continuous water inundation (coded A3); and regenerating *Melaleuca* forests subject to continuous water inundation (coded A4).

Forest inventory methods were used to conduct field sampling, data collection, and sample analysis (Preece et al., 2012) which were considerably cost-efficient and provided reliable results (Mohren et al., 2012). Stands, deadwood, understory, litter, and soil of the *Melaleuca* forests were conducted. Seven allometric equations, which are most common way to measure forest carbon stocks, were applied to calculate the above-ground and root biomass. The selected allometric equations were tested for statistical significance using the R Statistic Program. Using these equations, the average biomass was analyzed for typical *Melaleuca* forests. Detailed analysis methods are presented in the Supplementary.

3. Results and discussion

3.1. Characteristics of the typical Melaleuca forests in the study areas

The characteristics of the four typical *Melaleuca* forest types examined are summarized in Table 1. The stand densities of the four forest types were 2253, 2144, 1700, and 11625 trees ha^{-1} for the *Melaleuca* forest types A1, A2, A3, and A4, respectively (Table 1). The tree density of A4 was significantly higher than A1, A2, and A3 ($\chi^2 = 9.231$, $p = 0.026$) (Fig. 2a). Stand A4 was very dense and mostly dominated by trees with DBH < 10 cm (accounting for 91.4%), and had no trees with DBH ⩾ 30 cm because of the naturally uniform seed-regenerated trees. On the other hand, stands A1, A2 were similar, comprising trees with DBH from <5 cm to >40 cm, but mostly dominated by trees with 10 cm ⩽ DBH < 30 cm (accounting for 68.2% and 51.9%, respectively). Stand A3 was dominated by trees with 5 cm ⩽ DBH < 20 cm (accounting for 43.9%), and DBH < 5 cm (accounting for 41.2%) (Table 1). By observation, there were regenerated trees growing as scattered plots at the study sites which were properly consequence of different times of disturbances, and several bigger trees located around which were seed sources for regeneration.

Average DBH of all stand classes were 17.90, 19.91, 16.38, and 8.31 cm for A1, A2, A3, and A4, respectively (Fig. 2c). There was a significant difference in DBH in the four *Melaleuca* forest types ($\chi^2 = 9.867$, $p = 0.019$), but the post-hoc test shows that there was only significant difference in DBH of A2 and A4 (Supplementary).

Average total height of all stand classes were 15.61, 15.73, 9.26, and 9.35 m for A1, A2, A3, and A4, respectively (Fig. 2d). There was a significant difference between total height of the four forest types ($\chi^2 = 11.616$, $p = 0.0088$) (Supplementary). Furthermore, the tree density of the four forest types was generally very high, especially for forest class A4 (6000 individual stems/ha), which can contribute to a large biomass. The basal areas shown in Fig. 2b further confirm the large biomass of the forest types, particularly A1, A2, and A4 (the basal areas were 50.60, 48.29, and 40.57 m^2 ha^{-1}, respectively). There was a significant difference in basal areas in A1, A2, A3, and A4 ($F = 6.192$, $p = 0.0067$), particularly in A1 and A3 ($p = 0.0056$) (Supplementary). The basal area of A3 was only 22.27 m^2 ha^{-1}, which is much lower than A1, A2, and A4, but still a good amount of biomass.

The number of understorey species varied between the four forest types. The frequencies of sedges (*Cyperus* spp., *Schoenoplectus* spp., *Eleocharis* spp., *Lepironia* spp., *Lepidosperma* spp., *Carex* spp.), reed (*Phragmites australis*), and swamp water fern (*Blechnum indicum*) were high in forest types A1 and A3, where the conditions are always wet. The number of understorey species in A1 indicates that it is more diverse than A3. In drier areas, satintail grass (*Imperata* sp.) and several other grasses were the main species contributing the understorey of A2 (Table 1). Notably, forest type A4 has no understorey at all because of very dense stand canopy and thick coarse litter layer. Forest type A3 was regularly subjected

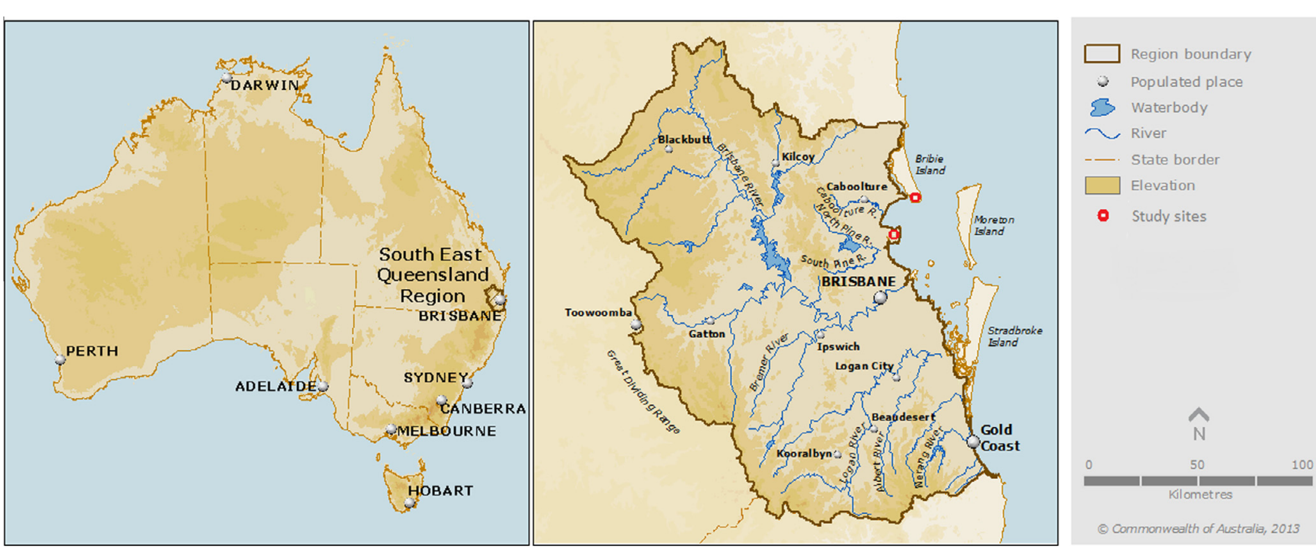

Fig. 1. The study locations in the study areas: Buckley's Hole Conservation Park and Hays Inlet Conservation Park, Queensland, Australia. *Source:* Maps were adopted from Bureau of Meteorology-Australian Government (Bureau of Meteorology, 2013).

Table 1
Major characteristics of four typical *Melaleuca* forests in the study areas.

Forest types	DBH classes	Standing trees								Understorey	Saturation levels
		Density		DBH		Basal area		Height			
		Mean (trees ha^{-1})	se	Mean (cm)	se	Mean (m^2 ha^{-1})	se	Mean (m)	se		
Primary *Melaleuca* forests subject to continuous water inundation (coded A1)	A1C0	201	180.6	3.48	0.22	na	na	5.26	0.26	*Cyperus* spp., *Schoenoplectus* spp., *Eleocharis* spp., *Lepironia* spp., *Lepidosperma* spp., *Carex* spp., *Phragmites australis*, *Blechnum indicum*	Seasonal and/or permanent inundation
	A1C1	467	212.2	6.92	0.24	na	na	10.08	0.47		
	A1C2	887	145.7	14.46	0.18	na	na	14.69	0.22		
	A1C3	650	85.6	23.74	0.19	na	na	18.05	0.16		
	A1C4	50	13.4	32.91	0.66	na	na	19.29	0.64		
	A1C5	na	na	na	na	na	na	na	na		
	All classes	2253	277.8	17.90	0.97	50.60	3.96	15.61	0.74		
Primary *Melaleuca* forests not inundated by water (coded A2)	A2C0	300	175.9	3.89	0.19	na	na	5.40	0.27	*Imperata* sp.	Never inundated
	A2C1	640	263.6	6.68	0.25	na	na	8.16	0.43		
	A2C2	576	161.7	14.89	0.24	na	na	15.31	0.20		
	A2C3	536	41.7	24.31	0.26	na	na	17.66	0.14		
	A2C4	68	32.5	33.27	0.71	na	na	18.46	0.21		
	A2C5	24	7.3	45.75	1.40	na	na	19.42	0.63		
	All classes	2144	501.8	19.91	2.27	48.29	3.50	15.73	0.83		
Degraded *Melaleuca* forests subject to continuous water inundation (coded A3)	A3C0	700	556.6	3.15	0.11	na	na	4.19	0.25	*Cyperus* spp., *Blechnum indicum*	Seasonal inundation
	A3C1	367	233.1	6.95	0.40	na	na	5.91	0.35		
	A3C2	380	87.2	14.62	0.41	na	na	9.75	0.50		
	A3C3	227	6.7	24.54	0.45	na	na	12.09	0.67		
	A3C4	27	13.0	36.19	2.35	na	na	15.01	1.87		
	A3C5	na	na	na	na	na	na	na	na		
	All classes	1700	663.0	16.38	2.26	22.27	1.98	9.26	0.08		
Regenerating *Melaleuca* forests subject to continuous water inundation (coded A4)	A4C0	6000	2,985.8	3.39	0.05	na	na	6.47	0.08	No understorey present because of dense stands, and thick coarse litter layers	Seasonal and/or permanent inundation
	A4C1	4625	1,395.5	6.28	0.09	na	na	8.76	0.09		
	A4C2	921	645.6	13.28	0.18	na	na	11.76	0.13		
	A4C3	81	67.1	23.01	0.62	na	na	14.72	0.25		
	A4C4	na	na	na	na	na	na	na	na		
	A4C5	na	na	na	na	na	na	na	na		
	All classes	11625	3751.0	8.31	2.33	40.57	7.17	9.35	1.35		

Note: C0: DBH < 5 cm; C1: 5 cm ⩽ DBH < 10 cm; C2: 10 cm ⩽ DBH < 20 cm; C3: 20 cm ⩽ DBH < 30 cm; C4: 30 cm ⩽ DBH < 40 cm; and C5: DBH ⩾ 40 cm.

to wildfire that burned the biomass of the understorey, but many understory species quickly re-grow after fire, particularly ferns (personal record).

3.2. Carbon stocks of the Melaleuca forest ecosystem

The carbon stocks of four *Melaleuca* forests types in the study area were 381.59, 278.40, 210.36, and 241.72 t C ha^{-1}, for A1, A2, A3, and A4, respectively (Fig. 3). There was a significant difference in carbon stocks in the four forest types ($\chi^2 = 8.3187$, $p = 0.0398$) (Supplementary). Carbon stocks of primary *Melaleuca* ecosystems (e.g. A1 and A2) were consistently higher than those of secondary ecosystems (e.g. A3 and A4), because a large amount of carbon stored in the biomass and soil components was released when these types of ecosystems were disturbed or degraded by natural and human activities such as wildfires, harvesting, and clearing.

3.3. Variability of six categories of carbon stocks in the Melaleuca forests

The carbon stocks of stands of the various forest types were 133.27, 133.96, 58.52, and 68.19 t C ha^{-1} for A1, A2, A3, and A4, respectively (Fig. 4a). There was a significant difference in stand carbon stock in these forest types ($\chi^2 = 40.582$, $p = 0.0001$) (Supplementary). The amount of carbon stored in primary *Melaleuca* forest (e.g. A1 and A2) was about twice that from the secondary *Melaleuca* forest (e.g. A3 and A4) because the primary forest had many more big trees than secondary forest. Carbon stocks of regenerating *Melaleuca* forests (e.g. A4) were greater than degraded *Melaleuca* forests (e.g. A3), because there was a much larger number of stems in regenerating forests than degraded forests (Table 2). These carbon stocks were similar to those found by other studies [e.g. the above-ground carbon stock of Asian tropical forests was 144 t C ha^{-1} (Brown et al., 1993); of primary and secondary swamp forests in Indonesia were 200.23 and 92.34 t C ha^{-1}, respectively (Rahayu and Harja, 2012)].

The carbon stocks of the understorey in the *Melaleuca* forests were 1.76, 1.06, 1.39, and 0.00 t C ha^{-1} for A1, A2, A3, and A4, respectively (Fig. 4b). There was no significant difference in understorey carbon stock in the four forest types ($\chi^2 = 0.228$, $p = 0.988$) (Supplementary). However, in forest type A4, understorey plants cannot grow because of the high density of the stands, which exclude light, and the thick coarse litter layer (accounting for 9.99 t C ha^{-1} of coarse litter) covering the forest floor.

The carbon stocks of deadwood in the *Melaleuca* forests were 44.70, 23.46, 41.32, and 30.13 t C ha^{-1} for A1, A2, A3, and A4 respectively (Fig. 4c). There was a significant difference in deadwood carbon stock in these forests ($\chi^2 = 1.697$, $p = 0.6376$), but pairwise comparisons show no significant difference (Supplementary).

The coarse and fine litter layers of the *Melaleuca* forest types contributed carbon stocks of 53.73, 8.33, 3.07, and 74.13 t C ha^{-1} for A1, A2, A3, and A4, respectively (Fig. 4d). There was a significant difference in total litter carbon stocks between the forest types ($\chi^2 = 36.137$, $p = 0.0001$) (Supplementary). The litter carbon stocks of A1 and A4 were not significantly different, but they were 6.5

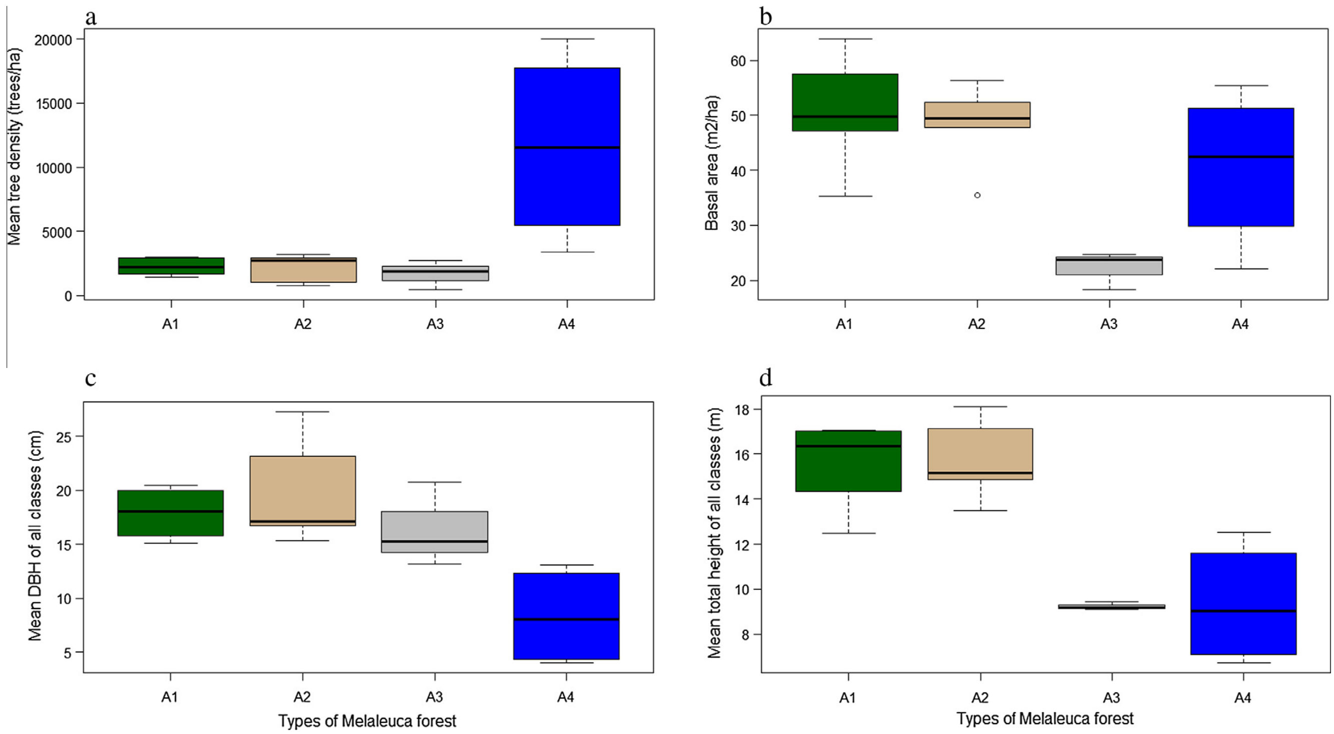

Fig. 2. Stand densities, basal areas, diameter at bread height, and total height of four *Melaleuca* forest types in the study area. *Note*: A1 = primary *Melaleuca* forests subject to continuous water inundation; A2 = primary *Melaleuca* forests not inundated by water; A3 = degraded *Melaleuca* forests subject to continuous water inundation; and A4 = regenerating *Melaleuca* forests subject to continuous water inundation.

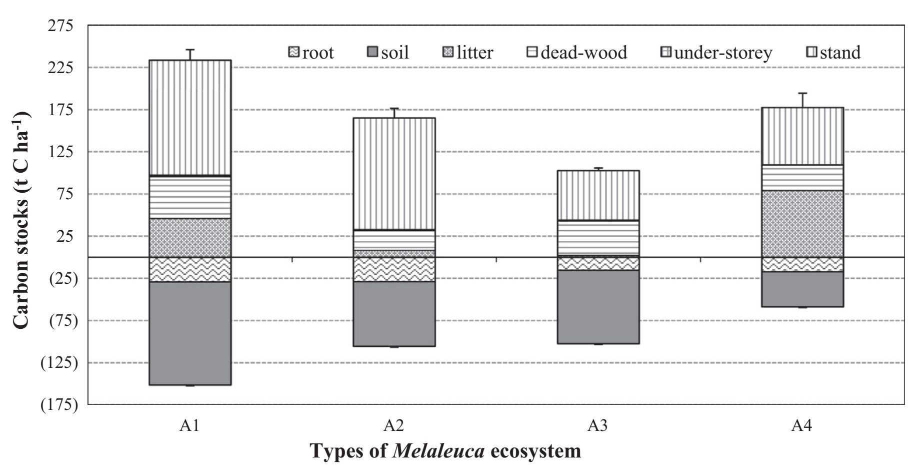

Fig. 3. Carbon stocks of four typical *Melaleuca* forests in the study areas. *Note*: A1 = primary *Melaleuca* forests subject to continuous water inundation; A2 = primary *Melaleuca* forests not inundated by water; A3 = degraded *Melaleuca* forests subject to continuous water inundation; and A4 = regenerating *Melaleuca* forests subject to continuous water inundation.

times and 8.9 times greater than A2, and 17.5 times and 24 times higher than A3, respectively.

The carbon stocks of coarse litter in these forest types were 17.51, 8.33, 3.07, and 9.99 t C ha^{-1}, while the carbon stocks of fine litter were 40.94, 0.00, 0.00, and 66.73 t C ha^{-1} for A1, A2, A3, and A4, respectively (Fig. 4e and f). Note that A4 was very dense regeneration with a lot of small stem (sapling) dead from self-thinning, which also contributed to a large amount of litter biomass. In addition, the litter was slow to decompose [e.g. leave litter of *Melaleuca* forest still remained 14% after 6 years experiment in Florida wetland (Rayamajhi et al., 2010); it took over 10 years to be completely decomposed (Tran, 2015)].

The carbon stocks of fine litter in *Melaleuca* forests subject to continuous inundation were far higher than those of woodlands and open forests in the Brigalow Belt South bioregion of Queensland [ranging from 1.0 to 7.0 t C ha^{-1}, with a mean of 2.6 t C ha^{-1} (Roxburgh et al., 2006)].

The carbon stocks of roots in the *Melaleuca* forests were 36.48, 36.59, 20.69, and 22.40 t C ha^{-1} for A1, A2, A3, and A4, respectively (Fig. 4g). There was a significant difference in root carbon stock in these forests (χ^2 = 82.765, p = 0.001). The carbon stocks of roots in A1 and A2 are more than 1.5 times higher than A3 and A4 (Supplementary). Generally, there is a relationship between the above-ground biomass and below-ground biomass of forest trees

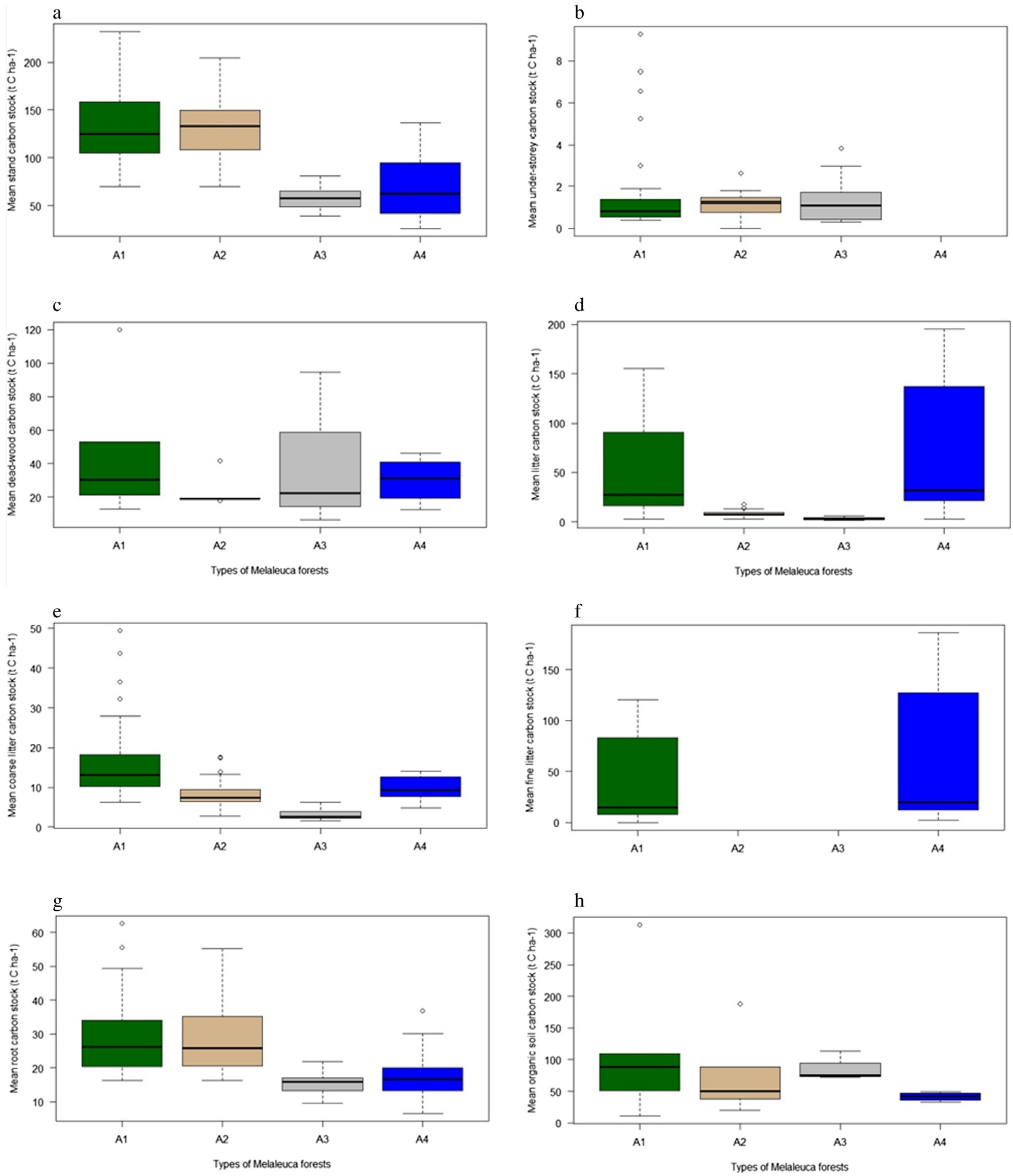

Fig. 4. Carbon stocks of the categories of four types of *Melaleuca* forests in the study area. Note: A1 = primary *Melaleuca* forests subject to continuous water inundation; A2 = primary *Melaleuca* forests not inundated by water; A3 = degraded *Melaleuca* forests subject to continuous water inundation; and A4 = regenerating *Melaleuca* forests subject to continuous water inundation.

characterized with a ratio of root and shoot biomass of around 0.3. For example, the root:shoot ratio of *Larixgmelinii* stand was 0.27 (Kajimoto et al., 1999); Sitka spruce was 0.23 (Farrell et al., 2007); *Eucalyptus* was 0.275 (Ribeiro et al., 2015); and of general forest was 0.25 (IPCC, 2003).

The amount of organic carbon in soil to 30 cm depth in the *Melaleuca* forests were 110.23, 76.79, 86.87, and 41.68 t C ha^{-1} for A1, A2, A3, and A4 respectively (Fig. 4h). There was a significant difference in organic soil carbon stock in these forest types ($\chi^2 = 4.308$, $p = 0.230$), but pairwise comparisons showed no

Table 2
Estimation of carbon stocks of *Melaleuca* forests and woodlands in Australia.

Forest types	Area in 2008[a] (000′ ha)	Carbon storage (Mt C)	Area in 2013[a] (000′ ha)	Carbon stocks (t C ha^{-1})	Amount of carbon storage (Mt C)
Melaleuca woodland	6654	na	5357	27.80[c]	148.92
Open *Melaleuca* forest	878	na	907	210.36–381.59	190.80–346.10
Closed *Melaleuca* forest	26	na	38	278.40–381.59	10.58–14.50
Total	7558	210[b]	6302	(na)	350.30–509.53

[a] Area of *Melaleuca* forests and woodlands reported by Montreal Process Implementation Group for Australia and National Forest Inventory Steering Committee (MIG, 2008, 2013).
[b] Carbon stocks of *Melaleuca* forest and woodlands estimated by Montreal Process Implementation Group for Australia and National Forest Inventory Steering Committee (MIG, 2008).
[c] Carbon stock calculated from estimation of Montreal Process Implementation Group for Australia and National Forest Inventory Steering Committee (MIG, 2008).

significant differences (Supplementary). These results are similar to those of other studies of soil carbon stocks up to 30 cm depth for primary and secondary *Melaleuca* forests: 106.00 t C ha^{-1} in wetlands (Page and Dalal, 2011), and 135.63 t C ha^{-1} in swamp forests in Indonesia (Rahayu and Harja, 2012). The organic carbon stocks in soil of *Melaleuca* forests are higher than those of woodlands and open forests up to 30 cm depth [ranging from 10.7 to 61.8 t C ha^{-1} (Roxburgh et al., 2006)], because most swamp *Melaleuca* always had greater amounts of litter (Fig. 4d–f) providing organic matter for soil. Otherwise, soil organic carbon likely had a high societal value [i.e. about US $ 132.70 per ton C (Lal et al., 2015)].

Overall, the carbon stocks of *Melaleuca* forests ranged from 210.36 t C ha^{-1} of degraded forests to 381.59 t C ha^{-1} of primary forests subject to inundation. The results contrast starkly with the current estimates of carbon storage in *Melaleuca* ecosystems published in Australia's National Greenhouse Gas Emissions Inventory Report [210 Mt C stored from 7.558 million ha of *Melaleuca* forests and woodlands, which equates to about 27.8 t C ha^{-1} (MIG, 2008, p. 117)]. Based on the data, Australia's 6.302 million ha of *Melaleuca* forests and woodlands contain between 350.30 Mt C and 509.53 Mt C (Supplementary). These carbon stocks are at least 7 times higher than the previous estimate by AGO.

3.4. Disturbances of carbon stocks in the Melaleuca forests

This study examined the effects of inundation, by comparing *Melaleuca* forest types A1 and A2. The inundation disturbance does not affect the carbon stocks of the stand, understorey, deadwood, root, or soil, but has a strong effect the litter carbon stock (Fig. 4d–f). Under saturated conditions (A1), both coarse and fine litter accumulated to significantly higher levels than in dry conditions (A2). Importantly, there was no fine litter in A2, which suggests that fine litter was mostly decomposed. These results are consistent with those of another in *Melaleuca quinquenervia* forests, which found that litter accumulation in a floodplain site was higher than in a riparian site (Greenway, 1994). de Neiff et al. (2006) also reported that leave litter decomposition in riverine forest was more rapid than that in oxbow lakes or palm swamp forest. It is therefore likely that longer inundation results in greater accumulation of fine litter in wetland forests. Conversely, drainage can deplete the litter carbon stocks of *Melaleuca* swamp ecosystems.

Kimmins (2004) reported that frequent fires can have a negative effect on forest stands, with little accumulation of decaying branches and logs, but an increase in standing dead trees. Frequent forest fires can also change the condition of mature *Melaleuca cajuputi* swamp forest in the wetlands of Southern Sumatra, Indonesia (Chokkalingam et al., 2007), which probably impacts the carbon stocks of the forests. In the study area, the *Melaleuca* forest type A3 gave us the opportunity to examine the effect of wildfire disturbance on carbon stocks. The results show that wildfires significantly depleted the carbon stocks of stands and litter of the *Melaleuca* ecosystems. The carbon stock of the total litter of A3 was significantly lower than A1 (Fig. 4d–f). It was likely that regular wildfires burned most of the coarse litter and reduced the sources of fine litter. Field data show that there was no fine litter at all in site A3. Consequently, the total carbon stock of A3 was equivalent to 55% of A1, that is likely the 45% of the carbon stock was lost due by disturbances involving wildfires and others which made A3 being degraded forests.

The results of this study indicate that fire may be more detrimental to carbon storage in Australian sclerophyll ecosystems than in other forests [i.e. fires reduced carbon stocks by only 9% in the Pacific Northwest national forests (Gray and Whittier, 2014)]. Our study results were consistent with other studies [e.g. natural disturbances can have a considerably impact on the carbon stocks of ecosystems (Bradford et al., 2013; Cole et al., 2014; Espírito-Santo et al., 2014); disturbances can reduce above-ground carbon stocks of disturbed forests by about 40% (Brown, 2014)]. We suggest that longer inundation in *Melaleuca* ecosystems lowers the risks of forest fires and increases the potential for carbon storage.

3.5. Estimation of carbon stocks of Melaleuca forests in Australia

Overall, the carbon stocks of *Melaleuca* forests in South-East Queensland ranged from 210.36 t C ha^{-1} for degraded forests subject to inundation to 381.59 t C ha^{-1} for primary forests subject to inundation. These results are very similar to the estimates of *Melaleuca* forests carbon stocks derived from secondary data by Tran et al. (2013a). The results contrast starkly with the current estimates of carbon storage in *Melaleuca* ecosystems published in Australia's National Greenhouse Gas Emissions Inventory Report [210 Mt C stored from 7.558 million ha of *Melaleuca* forests and woodlands, which equates to about 27.8 t C ha^{-1} (MIG, 2008, p. 117)]. Compared with other Australian native forests [i.e. the world's tallest hardwood forests was estimated to contain in excess of 1800 t C ha^{-1} (Keith et al., 2009)], the carbon stock of *Melaleuca* forests was about 4.7 times lower, but our results can contribute to improving the data on carbon storage from *Melaleuca* forests and woodlands in Australia. Based on our data, Australia's 6.302 million ha of *Melaleuca* forests and woodlands contain between 350.30 and 509.53 Mt C (Table 2). These carbon stocks are much higher than the previous estimate by the Australian government office (about 210 Mt C).

4. Conclusion

This paper considered the carbon stocks of *Melaleuca* forests, and carbon stocks of A1, A2, A3, and A4 were 381.59, 278.40, 210.36, and 241.72 t C ha^{-1}, respectively. Our data shows that the carbon stocks of *Melaleuca* forests from the sites sampled in Australia averaged 169.80 (±26.87) t C ha^{-1} in the above-ground biomass and 104.42 (±16.37) t C ha^{-1} in soil (0–30 cm depth) and

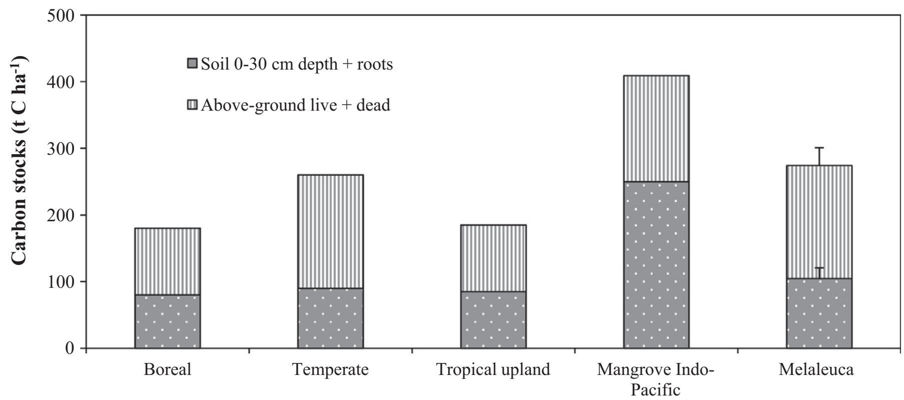

Fig. 5. Comparison of *Melaleuca* carbon storage with that of major global forests. *Sources:* Mean carbon storage of the ecosystems (Boreal, Temperate, Tropical upland, and Mangrove Indo-Pacific) was adopted from Donato et al. (2011), IPCC (2003) and Keith et al. (2009).

roots. Fig. 5 highlights how these are globally significant carbon storage. Carbon stores of *Melaleuca* forests are typically lower than those in mangrove forests in the Indian and Pacific Ocean regions, but similar to those of forests in temperate regions, and higher than boreal and tropical upland forests. In the peatlands of the Mekong Delta, *Melaleuca* forests store comparable amount of carbon to mangrove forests [i.e. carbon stock ranged from 544.28 to 784.68 t C ha^{-1} (Tran et al., 2015)].

Given that there are over 6.3 million ha of *Melaleuca* forest in Australia, there were from 350 to 509 Mt C stored in the nationwide. These estimates do highlight that more rigorous information is needed on the carbon stocks of *Melaleuca* forests. This will inform better land use planning and help determine what role *Melaleuca* forests should play in carbon farming initiatives such as those relating to avoiding emissions and forest conservation.

The study also examined how carbon stocks were influenced by disturbances such as inundation and wild fires. The carbon stock contribution from litter of inundated *Melaleuca* forests was 6.5 times higher than those not inundated by water. Forest fires significantly affected the carbon stocks that about 45% of carbon stocks in *Melaleuca* forests were probably lost as a result of wildfires.

Author contribution statement

D.B.T. and P.D. designed the field study and wrote the main manuscript text. D.B.T. collected the field data, analyzed data, prepared all figures, tables, and supplementary material. P.D. supported budget for field data collection and soil tests. All authors reviewed the manuscript.

Acknowledgement

This study was authorized to access and collect vegetation and soil samples in Buckley's Hole Conservation Park and Hays Inlet Conservation Park by the Department of Environment and Heritage Protection. All work was approved by the University of Queensland. The authors would like to thanks Dr. Tran Duy Hung; Mr. Nguyen Huu Thang, Mr. Nguyen Van Thuan, Mr. Trinh Nghia, and Ms. Tran Hong for their special assistance during the period of data collection at sites.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.foreco.2016.05.028.

References

Bernal, B., 2008. Carbon Pools and Profiles in Wetland Soils: The Effect of Climate and Wetland Type. Graduate School. The Ohio State University, Ohio, USA, p. 83.
Bernal, B., Mitsch, W.J., 2008. A comparison of soil carbon pools and profiles in wetlands in Costa Rica and Ohio. Ecol. Eng. 34, 311–323.
Bernal, B., Mitsch, W.J., 2012. Comparing carbon sequestration in temperate freshwater wetland communities. Glob. Change Biol. 18, 1636–1647.
Bradford, J.B., Jensen, N.R., Domke, G.M., D'Amato, A.W., 2013. Potential increases in natural disturbance rates could offset forest management impacts on ecosystem carbon stocks. For. Ecol. Manage. 308, 178–187.
Brown, A., 2014. Forest carbon: forest disturbance. Nat. Clim. Change 4, 533.
Brown, S., Iverson, L., Prasad, A., Liu, D., 1993. Geographical distributions of carbon in biomass and soils of tropical Asian forests. Geocarto Int. 8, 45–59.
Bureau of Meteorology, 2013. South East Queensland: Physical Information. Australian Government <http://www.bom.gov.au/water/nwa/2012/seq/contextual/physicalinformation.shtml>.
Chokkalingam, U., Suyanto, Permana, R., Kurniawan, I., Mannes, J., Darmawan, A., Khususyiah, N., Susanto, R., 2007. Community fire use, resource change, and livelihood impacts: the downward spiral in the wetlands of southern Sumatra. Mitig. Adapt. Strat. Glob. Change 12, 75–100.
Cole, L.E.S., Bhagwat, S.A., Willis, K.J., 2014. Recovery and resilience of tropical forests after disturbance. Nat. Commun. 5, 3906.
DAFF, 2010. Australian forest profiles: *Melaleuca*. In: Government, A. (Ed.). Department of Agriculture, Forest, and Fishery.
de Neiff, A.P., Neiff, J.J., Casco, S.L., 2006. Leaf litter decomposition in three wetland types of the Parana River floodplain. Wetlands 26, 558–566.
Donato, D.C., Kauffman, J.B., Murdiyarso, D., Kurnianto, S., Stidham, M., Kanninen, M., 2011. Mangroves among the most carbon-rich forests in the tropics. Nat. Geosci. 4, 293–297.
Espírito-Santo, F.D.B., Gloor, M., Keller, M., Malhi, Y., Saatchi, S., Nelson, B., Junior, R. C.O., Pereira, C., Lloyd, J., Frolking, S., Palace, M., Shimabukuro, Y.E., Duarte, V., Mendoza, A.M., López-González, G., Baker, T.R., Feldpausch, T.R., Brienen, R.J.W., Asner, G.P., Boyd, D.S., Phillips, O.L., 2014. Size and frequency of natural forest disturbances and the Amazon forest carbon balance. Nat. Commun. 5, 3434.
Farrell, E.P., Byrne, K.A., Tobin, B., Green, C., O'Shea, M., 2007. Above- and belowground biomass measurements in an unthinned stand of Sitka spruce (*Picea sitchensis* (Bong) Carr.). Eur. J. For. Res. 126, 179–188.
Gray, A.N., Whittier, T.R., 2014. Carbon stocks and changes on Pacific Northwest national forests and the role of disturbance, management, and growth. For. Ecol. Manage. 328, 167–178.
Greenway, M., 1994. Litter accession and accumulation in a *Melaleuca quinquenervia* (Cav.) S.T. Blake wetland in south-eastern Queensland. Aust. J. Mar. Freshwater Res. 45, 1509–1519.
IPCC, 2003. Good practice guidance for land use, land-use change and forestry. In: Penman, J., Gytarsky, M., Hiraishi, T., Krug, T., Kruger, D., Pipatti, R., Buendia, L., Miwa, K., Ngara, T., Tanabe, K., Wagner, F. (Eds.), IPCC National Greenhouse Gas Inventories Programme. Institute for Global Environmental Strategies (IGES) for the IPCC, Kanagawa – Japan.
Kajimoto, T., Matsuura, Y., Sofronov, M.A., Volokitina, A.V., Mori, S., Osawa, A., Abaimov, A.P., 1999. Above- and belowground biomass and net primary productivity of a *Larix gmelinii* stand near Tura, central Siberia. Tree Physiol. 19, 815–822.
Keith, H., Mackey, B.G., Lindenmayer, D.B., 2009. Re-evaluation of forest biomass carbon stocks and lessons from the world's most carbon-dense forests. Proc. Natl. Acad. Sci. 106, 11635–11640.
Kimmins, J.P., 2004. Forest Ecology: A Foundation for Sustainable Forest Management and Environmental Ethics in Forestry. Prentice-Hall, Upper Saddle River, N.J.
Lal, R., Negassa, W., Lorenz, K., 2015. Carbon sequestration in soil. Curr. Opin. Environ. Sustain. 15, 79–86.

MIG, 2008. Australia's state of the forests report: five-yearly report 2008. In: Biotext - Canberra (Ed.), Montreal Process Implementation Group for Australia. Bureau of Rural Sciences, Canberra.
MIG, 2013. Australia's state of the forests report 2013. In: Abares (Ed.), Montreal Process Implementation Group for Australia and National Forest Inventory Steering Committee, Canberra.
Mitra, S., Wassmann, R., Vlek, P.L.G., 2005. An appraisal of global wetland area and its organic carbon stock. Curr. Sci. 88, 25–35.
Mitsch, W., Bernal, B., Nahlik, A., Mander, Ü., Zhang, L., Anderson, C., Jørgensen, S., Brix, H., 2012. Wetlands, carbon, and climate change. Landscape Ecol., 1–15.
Mitsch, W., Nahlik, A., Wolski, P., Bernal, B., Zhang, L., Ramberg, L., 2010. Tropical wetlands: seasonal hydrologic pulsing, carbon sequestration, and methane emissions. Wetlands Ecol. Manage. 18, 573–586.
Mitsch, W.J., Tejada, J., Nahlik, A., Kohlmann, B., Bernal, B., Hernández, C.E., 2008. Tropical wetlands for climate change research, water quality management and conservation education on a university campus in Costa Rica. Ecol. Eng. 34, 276–288.
Mohren, G.M.J., Hasenauer, H., Köhl, M., Nabuurs, G.J., 2012. Forest inventories for carbon change assessments. Curr. Opin. Environ. Sustain. 4, 686–695.
Page, K.L., Dalal, R.C., 2011. Contribution of natural and drained wetland systems to carbon stocks, CO_2, N_2O, and CH_4 fluxes: an Australian perspective. Soil Res. – CSIRO Publ. 49, 377–388.
Preece, N.D., Crowley, G.M., Lawes, M.J., van Oosterzee, P., 2012. Comparing above-ground biomass among forest types in the Wet Tropics: small stems and plantation types matter in carbon accounting. For. Ecol. Manage. 264, 228–237.
Rahayu, S., Harja, D., 2012. A study of rapid carbon stock appraisal: average carbon stock of various land cover in Merauke, Papua Province. In: ICRAF-SEA, W.A.C. (Ed.), Technical Final Report. World Agroforestry Centre (ICRAF-SEA).
Rayamajhi, M.B., Pratt, P.D., Center, T.D., Van, T.K., 2010. Exotic tree leaf litter accumulation and mass loss dynamics compared with two sympatric native species in south Florida, USA. Eur. J. For. Res. 129, 1155–1168.
Ribeiro, S.C., Soares, C.P.B., Fehrmann, L., Jacovine, L.A.G., von Gadow, K., 2015. Aboveground and belowground biomass and carbon estimates for clonal Eucalyptus trees in Southeast Brazil. Rev. Árvore 39, 353–363.
Roxburgh, S.H., Mackey, B.G., Dean, C., Randall, L., Lee, A., Austin, J., 2006. Organic carbon partitioning in soil and litter in subtropical woodlands and open forests: a case study from the Brigalow Belt, Queensland. Rangeland J. 28, 115–125.
Tran, D.B., 2015. A study of the carbon stocks of Melaleuca forests in the coastal regions of Southern Vietnam and South East Queensland Australia. In: The University of Queensland, School of Geography, Planning and Environmental Management.
Tran, D.B., Dargusch, P., Herbohn, J., Moss, P., 2013a. Interventions to better manage the carbon stocks in Australian *Melaleuca* forests. Land Use Pol. 35, 417–420.
Tran, D.B., Dargusch, P., Moss, P., Hoang, T.V., 2013b. An assessment of potential responses of *Melaleuca* genus to global climate change. Mitig. Adapt. Strat. Glob. Change 18, 851–867.
Tran, D.B., Hoang, T.V., Dargusch, P., 2015. An assessment of the carbon stocks and sodicity tolerance of disturbed *Melaleuca* forests in Southern Vietnam. Carbon Balance Manage. 10, 1–14.