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Viewpoint

Interventions to better manage the carbon stocks in Australian *Melaleuca* forests

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ABSTRACT

Forests and woodlands dominated by tree species of the genus *Melaleuca* cover around 7,556,000 ha in Australia and predominantly occur as wetland ecosystems. In this *Viewpoint*, we use published secondary data to estimate that there is likely to be between 158 tC/ha and 286 tC/ha stored in *Melaleuca* forests. These estimates are at least five times greater than the previous estimate made by the Australian Government (about 27.8 tC/ha). There are 2.1 million ha of protected *Melaleuca* forest which likely stock between 328 M tC and 601 M tC; equivalent to between 2.7% and 5.0% of total carbon storage of all Australian native forests. These estimates are significant because it appears that carbon stocks in *Melaleuca* forests are currently dramatically under-estimated in Australia's national greenhouse gas emissions inventory reported under the United Nations Framework Convention on Climate Change (UNFCCC). Whilst the precision of the estimates is limited by the availability of rigorous primary data, we also argue that the estimates are indicative and meaningful, and this synopsis highlights the fact that this forest type should be considered a significant carbon store nationally and globally.

Rationale

Melaleuca forests occur over a very broad area of Australasian and Southeast Asian countries (Blake, 1968; Brown et al., 2001; Craven, 1999). Within Australia, there are 7,556,000 ha of *Melaleuca* forests and woodlands (naturally occurring), equivalent to 5% of the total forest area (DAFF, 2010; MPI, 2008) (a distribution map of the *Genus* and example photographs of *Melaleuca* forests are provided in supplementary material – Supplementary 1 and 2). They are 7.7 and 2.3 times greater than the area of mangrove forests and rainforests in the country, respectively. *Melaleuca* forests in Australia mostly occur in a sub-tropical and tropical woodland habit (~97%) with around 84% of the forest type located on publicly owned land and the remainder on privately owned land (DAFF, 2010; MPI, 2008). Most of the publicly owned land covered by *Melaleuca* forests is leasehold land which is currently used for cattle grazing. Only about 4500 ha of plantations of *Melaleuca* have been established for the production of tea tree oil (RIRDC, 2006). Of the total area of this forest type in Australia, over 5,698,000 ha are located in the state of Queensland, of which 2,104,000 ha are located in protected areas such as national parks (DAFF, 2010; MPI, 2008). *Melaleuca* forests in Australia are predominantly wetland forests, and occur in lacustrine and palustrine land systems (e.g. Supplementary 2). Common species of the genus *Melaleuca* in Australia include *Melaleuca viridiflora*, *Melaleuca leucadendra*, *Melaleuca argentea*, *Melaleuca quinquenervia*, *Melaleuca nervosa*, *Melaleuca preissiana*, and *Melaleuca rhaphiophylla*.

This paper collates secondary data on the carbon stocks[1] of *Melaleuca* forests in Australia, and estimates the current financial value of the carbon contained in these forests. Importantly, there is literally only a handful of papers and reports in the public domain that deal with the carbon stocks of *Melaleuca* forests. A discussion on carbon stocks in *Melaleuca* forests in Australia is therefore both timely and important for several reasons. Firstly, this forest type is likely to contain carbon stocks of global significance, because many freshwater wetlands are known to store high amounts of carbon [e.g. the rate of carbon accumulation estimated in the

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[1] Carbon stocks refer to those stores of carbon fixed within a forest ecosystem including standing, understorey, litter and deadwood biomass, and soil organic carbon that if released in their gaseous states would become greenhouse gas emissions [1 tC = 3.67 tonnes carbon dioxide equivalent (tCO_2e)].

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Quercus palustris forested wetland community in temperate region of USA was 4.73 tC/ha/yr (Bernal and Mitsch, 2012), and in the *Cyperus papyrus* tropical wetland in Uganda was 4.8 tC/ha/yr (Saunders et al., 2007)]. However, the carbon stocks of *Melaleuca* forests, including any change or disturbance to those stocks, appears to have been inadequately reported in Australia's national greenhouse gas emissions accounts, which is required under the Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC). For example, the Australian Government estimated in 2004 that there was 210 million tC in Australian *Melaleuca* forests, equivalent to around 27.8 tC/ha (MPI, 2008, p. 117). This paper shows why this is likely to be a dramatic underestimate of the amount of carbon stocks in *Melaleuca* forests. Secondly, *Melaleuca* forests in Australia also have high conservation values [e.g. biodiversity, and as indigenous cultural and heritage sites (EPA, 2005)], high vulnerability but aggressive responses of adaptation to climate change (Tran et al., 2012), and occur in localities under pressure from mining and urban development. Management that aims to conserve the carbon stocks of *Melaleuca* forests should also work to conserve the ecological value of those forests. However, the development and planning controls in many jurisdictions in Australia do not give the carbon stocks in the soil components of *Melaleuca* forests adequate consideration, despite this pool containing substantial amounts of carbon in some *Melaleuca* forest types (Supplementary 4). Focus is primarily on the vegetative aspects of *Melaleuca* ecosystem, and little consideration is given to the development and drainage of areas of these forest types that might be cleared, even though such sites probably contain very large quantities of soil carbon.

Deriving an estimate of carbon stocks

Here we use published data and International Panel of Climate Change (IPCC) carbon stock estimation methods to derive an estimate of the carbon stocks of *Melaleuca* forests in Australia. As noted above, there is a stark paucity of published information on the carbon stocks of *Melaleuca* forests in Australia and this makes deriving a reliable estimate using existing data problematic. The estimate presented here needs to be considered in this context, and that whilst it is limited by lack of existing data, our estimate highlights the likely significance of *Melaleuca* forests as a carbon store and we use the estimate to call for more research and better policy intervention on this topic.

As per IPPC guidelines (IPCC, 2003), the carbon fraction of dry matter in above-ground biomass and litter can be assumed to be 50% and 45%, respectively. There is no published Australian data related to the biomass in the understorey and deadwood components of *Melaleuca* forests in Australia, so these two IPCC categories were not included in the estimates. The amount of carbon in *Melaleuca* forests was estimated as follows:

$$\text{C density}\,(\text{tC/ha}) = \text{C standing biomass} + \text{C litter biomass} + \text{C soil organic.}$$

Soil organic carbon (SOC) content was estimated using the equation:

$$\text{SOC} = \text{Depth}\,(\text{m}) \times \text{bulk density}\,(\text{g cm}^{-3}) \times \text{C}\,(\%) \times 100$$

where the SOC formular derives from IPCC, and 100 is the default unit conversion factor.

Only one publication has to date presented an estimate of the amount of tree biomass in *Melaleuca* forest ecosystems in Australia based on forest inventory data collected in the field. Finlayson et al. (1993) estimated that the average above ground dry biomass in *Melaleuca* forests is approximately 132 t/ha [the value was converted from the original fresh biomass value by Van et al. (2000), and did not include root mass]. Additionally, based on the values of diameter at breast height and tree densities from Franklin et al. (2007), biomass of five species including *M. argentea*, *M. cajuputi*, *M. dealbata*, *M. leucadendra* and *M. viridiflora* were converted and estimated accounting for approximately 168 t/ha, 81 t/ha, 54 t/ha, 96 t/ha, and 80 t/ha, respectively. These compare with introduced *Melaleuca* forests in Florida USA, for which the estimates are 181 t/ha (Van et al., 2000), and 331 t/ha (Rayamajhi et al., 2008) (Supplementary 3). Assuming that the estimates from values of Franklin et al. (2007) (with the lowest and highest records 54 t/ha and 168 t/ha, respectively) are representative of the above ground biomass in *Melaleuca* forest ecosystems in Australia, then the typical carbon stocks in tree biomass in *Melaleuca* forests is likely to be between 27 tC/ha and 84 tC/ha.

Four studies have examined the dynamics of litter fall (leaves, bark, fruit and branches) and accumulation in *Melaleuca* forests. Congdon (1979), Finlayson et al. (1993) and Greenway (1994) examined litter dynamics in *Melaleuca* forests in Australia, while Rayamajhi et al. (2006) examined the litter dynamics in *Melaleuca* forests in Florida, USA. The rate of litter fall in *Melaleuca* forests in Australia has been estimated to be between 7.00 and 7.67 t/ha/yr in the floodplains of Northern Queensland (Finlayson et al., 1993) and Southeast Queensland (Greenway, 1994), respectively. Litter accumulation was 23.20 and 34.57 t/ha/yr on the floodplain and the forest floor, respectively, based on data from eight 0.0625 m^2 quadrat samples at each site in Native Dog Creek/Logan River floodplain, southeast Queensland (Greenway, 1994). Greenway (1994) also reported various indicators of high carbon content in the forest litter components of *Melaleuca* forests (notably C:N = 60:1, C:P = 1400:1 for litter with decay size $\geq$5 mm, and C:N = 25:1 and C:P = 300:1 for litter decay size <5 mm). This probably reflects slow rates of litter decomposition. For instance, Rayamajhi et al. (2006) recorded that after 322 weeks, 14% of litter fall had not decomposed in the Floridian *Melaleuca* forests.

If we assume that the estimates of accumulated forest litter range from 7.00 t/ha/yr to 34.57 t/ha/yr in Australian sites [as per the studies of Finlayson et al. (1993) and Greenway (1994)] are representative of the amount of accumulated forest litter in *Melaleuca* forests, then it is reasonable to estimate that the typical carbon content in the litter of *Melaleuca* forests is between 3.15 tC/ha and 15.56 tC/ha.

The following estimates of soil carbon stocks are based on the results of soil analyses reported by the Queensland Wetlands Programme using samples taken in *Melaleuca* forest sites located in different parts of Queensland, Australia. The soil organic carbon content (C%) and C:N ratios of the soil samples are presented in Supplementary 4. Studies on soil properties conducted around Australian wetlands show that soil bulk density ranges from 1.5 g/cm^3 at 0.1 m depth in the coastal lowlands of southeast Queensland (Costantini, 1995), to 1.6 g/cm^3 at 1 m depth in woodland-open forest landscape within the Brigalow Belt South bioregion of Queensland (Roxburgh et al., 2006), to 0.55 g/cm^3 at 0.25 m depth in hydrosols in Darwin Harbour (Hill and Edmeades, 2008); the latter being consistent with other reported values from North Queensland (McKenzie et al., 2000), and the Hunter River estuary in Southeast Australia (Howe et al., 2009). Therefore, assuming that *Melaleuca* forest soils have a bulk density of ranging from 0.55 g/cm^3 (Hill and Edmeades, 2008) to 0.8 g/cm^3 (personal record) with mean average carbon concentration of 7.75% (Supplementary 4), and these data are representative of *Melaleuca* forest soils, the typical soil carbon content in at 0–30 cm depth of *Melaleuca* forests in Australia is likely to be range between 128 tC/ha and 186 tC/ha. These estimates are consistent with those reported by Page and Dalal (2011) for soil carbon stocks in wetlands of other vegetation types in Queensland (from 12 to 557 tC/ha).

In summary, the typical carbon stocks in Australian *Melaleuca* forests range from 158 tC/ha to 286 tC/ha. This estimate does not include understorey, deadwood, root and other under-ground biomass components and therefore is likely to be an underestimate of actual levels of carbon stocks. The estimates also appear reasonable when compared to data from other forest types, particularly natural *Eucalyptus* forests in Australia and while there is clearly a lack of precision in our estimate of carbon stocks due to the paucity of data available, we are confident that they provide an indicative estimate. In Tasmanian forest landscapes, the above-ground carbon density of dry forests, wet forests (eucalypt and non-eucalypt), wet eucalypt forests, mature eucalypt forests, mature dry eucalypt forests, and mature wet eucalypt forests was 118 tC/ha, 185 tC/ha, 222 tC/ha, 179 tC/ha, 121 tC/ha, and 232 tC/ha, respectively (Moroni et al., 2010). Additionally, mean soil C stocks in Tasmanian native forests was 97 and 193 tC/ha at 0.3 m and 1.0 m depth, respectively (Cotching, 2012). The total carbon stocks of the *Eucalyptus* forests of South-eastern Australia has been estimated at 640 tC/ha, of which soil organic carbon accounts for 280 tC/ha, with the forest biomass accounting for 360 tC/ha (Mackey et al., 2008). Moreover, Keith et al. (2009) estimated that there is in excess of 1800 tC/ha in the world's tallest hardwood forests dominated by *Eucalyptus regnans*.

It also appears that previously published estimates of *Melaleuca* carbon stocks [i.e. about 27.8 tC/ha (MPI, 2008, p. 117)] are likely to be a gross underestimate of actual stocks. That estimate is seven times lower than carbon stocks of the tropical savannah in northern Australia [204 tC/ha, of which soil organic carbon content (depth 0.1 m) accounts for 151 tC/ha and above-ground accounts for 53 tC/ha (Chen et al., 2003)].

Policy interventions and future research

The *Melaleuca* genus has a wide geographic range within Australia, with substantial areas in remote locations that are difficult to access. It is also appears that there has been a perception amongst land managers and policy makers in Australia to date that *Melaleuca* forests offered little commercial value other than for grazing purposes and honey production in some localities. Partly because of these reasons, the estimation of carbon stocks in *Melaleuca* forests in Australia has been attributed a low priority. We acknowledge that the carbon storage estimates for *Melaleuca* forests that have been made and reported in this paper are broad and do not rigorously reflect the variability and complexity across the total area of Australian *Melaleuca* forests. However, we also argue that the estimates are indicative and meaningful, and highlight the need for future research and policy action.

In addition to developing better information related to estimating the mass of carbon stored in *Melaleuca* forests as 'stocks', future research should also be directed into the processes that influence the dynamics of those stocks. The carbon dynamics in Australian *Melaleuca* forests are likely to be complex, involving a range of factors including flooding, sediment accretion, litter deposition and decomposition, salinity, acidity, pollution and drainage. There is a pressing need for further research to help better understand these dynamics.

One of the key opportunities for enhancing the conservation of *Melaleuca* forests in Australia is to develop carbon offset opportunities, through which the avoidance of emissions and rehabilitation of carbon stocks in those forests is financially rewarded. However, fundamental to the successful design of such mechanisms, is a sound understanding of the processes that influence the dynamics of carbon stocks, and an ability to reliably estimate the amount of emissions avoided and the yield of carbon sequestered, through conservation activities. Recent developments in climate policy in Australia [notably the Carbon Credits Act and Carbon Farming Initiative (Australian Government, 2011)] that encourage the development of innovative carbon offset project designs, might also be possible in *Melaleuca* forests, and make discussion of these issues particularly topical and timely. Under the current rules of the Carbon Farming Initiative, it is difficult to have an offset methodology that focusses on avoiding emission losses from deforestation and degradation related activities approved. However, it is believed that such methodologies can be justified under certain circumstances, particularly where issues of leakage and permanence can be reasonably addressed. Given the features of *Melaleuca* forests in Australia in regards to their distribution, land tenure and disturbance pressures, a creative and rigorous methodology for *Melaleuca* forests is entirely plausible and worthy of consideration.

Emission from urban development activities is likely an omission or inadequacy in Australian national greenhouse inventory systems. Under the Australian National Carbon Accounting System, emission arisen from land use change is mainly from deforestation (DCCEE, 2012), and deforestation is from the conversion of land to cropland and grassland, but land use change from urbanisation is obviously excluded (AGEIS, 2012). Moreover, urban development activities are not in the List of Australian and New Zealand Standard Industrial Classification (NPI, 2006).

In addition, an understanding of the carbon stocks and dynamics also has important implications in relation to the approval of urban development and the environmental conditions placed on such developments. Ignoring the carbon stocks and dynamics in *Melaleuca* ecosystems may result in substantial carbon emissions, and these costs need to be taken into account in any future development activities. A current example is the Stockland Caloundra development, which proposes 'to construct and operate a master planned community catering for up to 50,000 residents on Queensland's Sunshine Coast' (DSEWPaC, 2011). In a report of more than 500 pages relating to environmental impact analysis and plans for this proposed development, the topic of carbon stocks in the soils of the site's *Melaleuca* forest ecosystems is not mentioned. Much of the urban development that has taken place in southeast Queensland over the last 20 years in the Gold Coast and Sunshine Coast regions, has taken place on land previously covered by *Melaleuca* forests. Most carbon stored on these sites would have been converted to atmospheric greenhouse gas emissions through deforestation, forest degradation and wetland drainage that took place in the early stages of urban development. The impacts of these emissions on climate change, and the potential financial value of the carbon stores in the forests systems, were not, and are still not, considered as important issues for planners and developers.

There is an urgent need for more research into the carbon stocks of Australian *Melaleuca* forests. Field studies are required to more rigorously assess the carbon stocks and dynamics of those stocks in the forest type. Furthermore, *Melaleuca* forests are at high risk from impacts of climate change like sea level rise (Australian Government, 2009; Bowman et al., 2010), and bush fires (Crowley et al., 2009; Franklin et al., 2007)]. Policy makers need to consider various interventions including carbon offset development initiatives that give more attention to this important carbon-rich forest type in conservation and land management decisions.

Note that the authors are currently undertaking a research project that seeks to verify some of the carbon stock estimates presented in this paper. Data on carbon stored in biomass, soil and litter is being collected from a series of different types of *Melaleuca* forests in South-east Queensland to not only assist in verifying the estimates presented in this paper but also help better understand the dynamics of carbon sequestration and carbon loss in forests with different water level profiles, soil types and degrees of disturbance. There has been growing recognition in recent years in the climate policy and natural resource policy discourse of the importance of various wetland types (particularly in regards to tropical peat-lands and mangroves) as sizeable and vulnerable carbon stores. The management of these land systems and their carbon stores have become a critical issue for sustainable land management and related policy intervention. The estimates we present in this paper highlight the importance of *Melaleuca* forests in Australia as another globally important wetland carbon store and reinforce the need to grow awareness amongst policy-makers around the world for more research into the dynamics of carbon sequestration and carbon loss in other poorly understood wetland types.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.landusepol.2013.04.018.

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