# An Eco-cultural Investigation of *Melaleuca* spp. Dieback in North-East Arnhem Land, Australia

Bachelor of Environment (Biology and Environmental Management)

Thesis submitted in accordance with the requirements of the Master of Research

Department of Environmental Sciences

Macquarie University

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# Declaration

I hereby declare this thesis has not been previously submitted to any other institution or university for a higher degree. This thesis is comprised entirely of my own work, except where acknowledged otherwise. Ethical aspects of this thesis have been approved by the Macquarie University Human Research Ethics Committee (Reference No. 5201500755).

Daniel Richard Sloane

October 10th 2016

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## Abstract

Recently, Traditional Owners (TOs) of the Laynhapuy Indigenous Protected Area (IPA) in the Northern Territory, Australia, expressed concern about the dieback of culturally significant coastal *Melaleuca* spp. (paperbark). Congruous with International obligations, mutual respect and best research practice on Aboriginal land, a collaborative eco-cultural approach was used to identify potential causal factors of dieback to inform local decision-making. Socio-cultural research was conducted with senior TOs through semi-structured interviews and ecological approaches were applied to investigate potential correlates of *Melaleuca* spp. dieback. Quadrats were sampled in "alive" and "dead" *Melaleuca* patches at five floodplains in the Laynhapuy IPA to determine differences in: demography, species richness, feral ungulate [buffalo (*Bubalis bubalis*) and pig (*Sus scrofa*)] damage, surface and sub-surface soil pH and salinity. Remarkably, the two research approaches similarly suggested that about 70% of *Melaleuca* dieback was attributed to combinations of salinity and feral ungulate damage. Unexplained variation in dieback was suggested by TOs as possibly due to cyclone events and by ecological research as possibly acid sulfate soils, with implications for future research. The benefits of using both socio-cultural and ecological approaches were important for understanding the dieback as well as to empower local decision-making and ongoing research, highlighting the value of cross-cultural collaborations.

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# 1 Introduction and thesis aims

## 1.1 Indigenous land and sea management

Australia is a signatory to the United Nations Convention on Biological Diversity (CBD). This international agreement pledges all signatories to preserve and enhance the biological diversity of their nations. Of equal importance within the convention is the mandate to preserve the traditional practices, culture and knowledge of the signatories' Indigenous peoples (United Nations, 1992). Aboriginal people have inhabited Australia for at least 50,000 years (Roberts *et al.* 1994). At the time of European colonisation at least 250 language groups occupied different estates across the entire continent (McConvell & Thieberger, 2006). During British colonisation of Australia, these local languages and associated cultures were often restricted and suppressed (McConvell & Thieberger, 2001) and as a result much of Aboriginal culture and Indigenous ecological knowledge (IEK) has been lost, although there is currently an Indigenous language and culture revival movement occurring in Australia. In the face of growing environmental crises, global environmental leaders are turning again to Indigenous people as their culture embodies tens of thousands of years of local knowledge accumulated through direct contact and sustainable living with their ancestral lands. Indigenous people have recently made significant contributions to fisheries (Plagányi *et al.* 2013; Allen *et al.* 2009) and forest management (Berkes, 2012) for example, in many parts of the world. Conservation of Indigenous culture therefore represents a broader effort by humanity to preserve the myriad knowledges that have arisen throughout the course of human history, and to benefit from the associated lessons that are increasingly being recognised as relevant in contemporary environmental research, conservation and management (WCED, 1987).

Contemporary national responsibility to preserve and enhance culture and biodiversity manifests itself in many forms. In Australia, one of the most obvious examples is the National Reserve System (NRS). Under this system, several different types of reserves are recognised including Indigenous protected areas (IPAs). The IPA program was established in 1997 and was founded on voluntary declarations of land by Traditional Owners to become part of the NRS. The Australian Government funds IPA management largely according to International Union for Conservation of Nature (IUCN) management categories V and VI which in addition to conservation objectives, also allow for the sustainable use of natural resources by Aboriginal people (Szabo & Smyth, 2003). IPAs currently make up about 44.6% of Australia's NRS (Australian Government Department of the Prime Minister and Cabinet, 2016; Figure 1) and Indigenous land and sea management (ILSM) is considered the fastest growing sector of Australia's conservation agenda (Hill *et al.* 2013). To complement the IPA program, the Indigenous Ranger initiative (Working on Country program) was established by the Australian Government in 2007, and in 2016, supported over 777 Indigenous ranger positions (Australian Government Department of the Prime Minister and Cabinet 2016). ILSM offers a propitious niche for Aboriginal people. Land "management" is not only a culturally meaningful activity but one which also offers socio-economic benefits in contemporary Australia (Moorcroft, 2015).

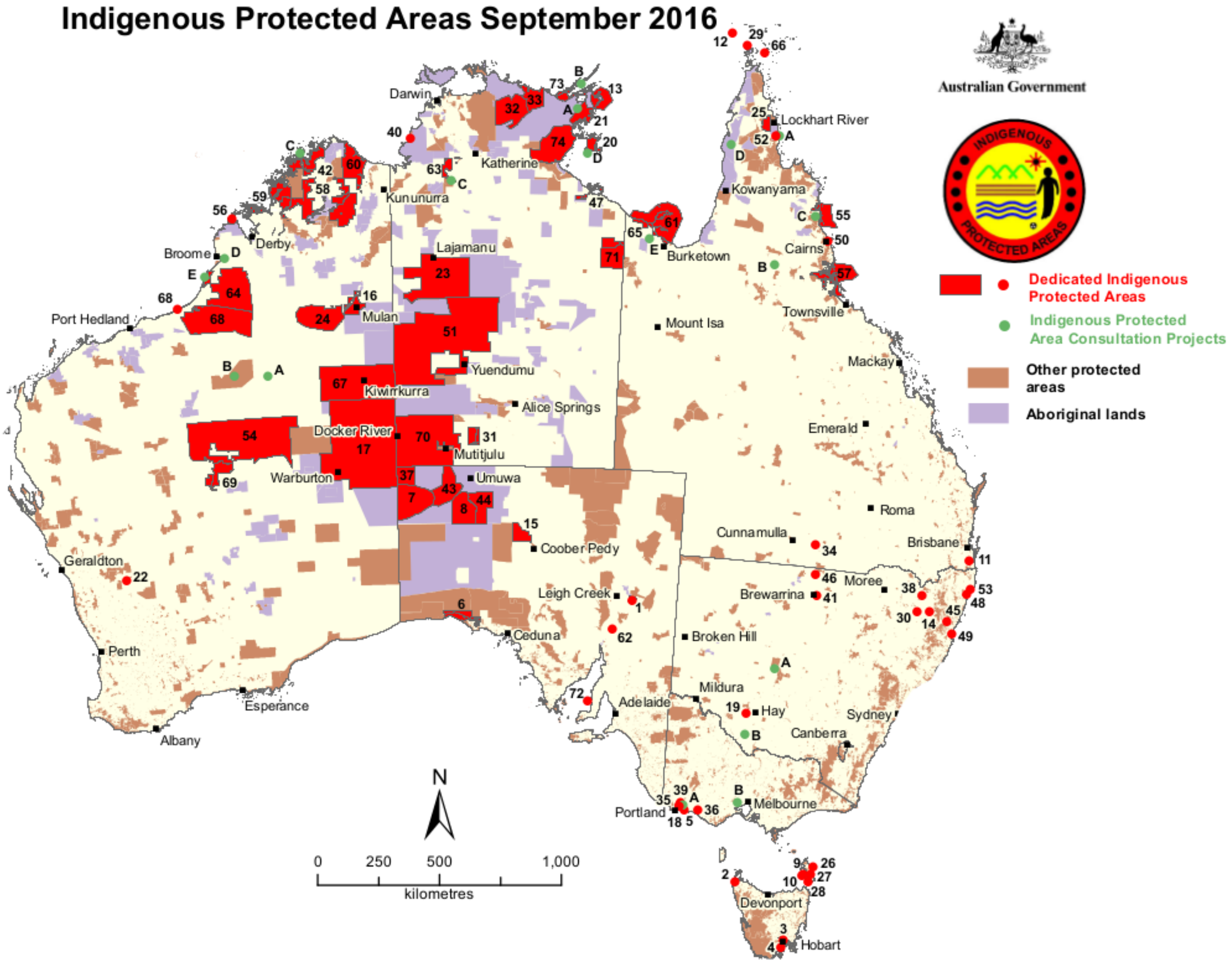


**Figure 1 –** Indigenous Protected Areas, Aboriginal lands and the remainder of the National Reserve System, 2016. Adapted from: Commonwealth of Australia Department of the Environment (2016).

Traditional owners (TOs) across Australia face a slew of ecological challenges for the management of Country including invasive species, changed fire regimes, climate change and depopulation (Altman *et al.* 2007; Sithole *et al.* 2007; Woinarski *et al.* 2007). Aboriginal Ranger groups and IPAs often deploy combinations of traditional and contemporary land management methods (Ens *et al.* 2015; Robinson & Lane, 2013; Ens *et al.* 2012; Preuss & Dixon, 2012) and continue to make significant contributions to environmental management and related research in Australia (Ens *et al.* 2015). Widely known are the contributions made by Aboriginal people to fire management (especially in northern Australia), cultural heritage maintenance, threatened species management and invasive species control (Ens *et al.* 2015). Climate change is also an increasing concern for Aboriginal people (Zander *et al.* 2013; Petheram *et al.* 2010), especially in relation to their dependence on water (Opare, 2016) and for those inhabiting coastal regions (Green *et al.* 2009).

## 1.2 Cross-cultural research

Aboriginal TOs working on their ancestral lands notice change and are informed about environmental change through interpersonal knowledge transmission (Muller, 2014). Aboriginal people often want to pursue research questions that have arisen out of community concerns rather than from external scientists (Smith, 2012; Allen *et al.* 2009). When aspirations and interests from the two parties converge, research questions are increasingly being pursued using a cross-cultural (or two-way/both ways) approach (Ens, 2012; Ens & McDonald, 2012; Preuss & Dixon, 2012). Indigenous people want quality science (Smith, 2012; Allen *et al.*, 2009), but past approaches to research concerning Indigenous people has often failed to adequately consider local interests and aspirations (Howitt, 2001). As such, progressive research involving Indigenous people should be done 'in the right spirit', meaning that researchers should work closely with Indigenous people to ascertain their interests in and expectations of research so that mutually beneficial outcomes can be reached (Smith, 2012; Allen *et al.* 2009). In addition, the integration of diverse knowledge types may result in an increased likelihood of producing effective solutions to environmental issues (Patterson *et al.* 2013). For example Ens *et al.* (2016) have used cross-cultural approaches to raise community awareness about the impacts of feral ungulates and protect culturally significant wetlands.

The study presented in this thesis utilised an eco-cultural approach to research. An eco-cultural perspective supports an integrated ontology[1] of landscapes, (akin to Ens *et al.* 2016; Pellat & Gedalof, 2014; Burger, 2011; Rapport & Maffi, 2011; Harris & Harper, 2000) and in this case, of particular species in those landscapes. This perspective prioritises both cultural and ecological integrity for the unified maintenance of human and ecosystem values (Rapport & Maffi, 2011). In the present study, this resulted in the development of approaches that addressed the cultural and ecological aspects of the study with methods well suited to both.

Yolŋu (local Aboriginal people of NE Arnhem Land) and Western ontologies are distinct. Western ontologies tend to be dominated by categorical thinking that compartmentalises information about the world into silos of knowledge (Howitt, 2001). This may have instigated the pervasive conceptual nature – culture binary that now strongly influences resource management paradigms and practices (Worster, 2008; Scott, 1998) leading to a utilitarian view of natural resources (Mathews, 1994) which is often devoid of a deeper, perhaps even spiritual, connection to the ecologies interlinked with human lives (Berkes, 2012). This contrasts with Yolŋu ontology which follows much more relational thinking (Howitt, 2001) that recognises the connectedness of all things, resulting in an understanding of nature and culture as an inextricable, holistic entity (Weir *et al.* 2013; Rose, 1996). This constructs an arguably more realistic representation of reality in which humans are part of the natural world, not abstracted from it (Bawaka Country *et al.*, 2013). Marika-Munungiritj (1991) described how non-Indigenous people can learn from Yolŋu by adopting the wisdom that knowledge comes from the land not books.

Many Indigenous and non-Indigenous people recognise that Indigenous and non-Indigenous knowledge, almost

[1] Ontologies are related to the nature of being. They may be described as ways of living and knowing about the world.

by virtue of their differences, may be complementary for environmental research (Berkes *et al.*, 2000; Huntington, 2000). Yolŋu people have recognised the potential for ontological complementarity and described the knowledge and methods of balanda/ŋapaki (non-Aboriginal) and Yolŋu coming together as being like freshwater meeting saltwater (Yunupingu, 1991). Still, power relations in cross-cultural collaborations are often made invisible (Muller, 2014) and past Western research practices involving Indigenous people have been typified by subjugation of Indigenous knowledge, practices and concerns whilst ignoring the enduring history of Indigenous people and their relationships with, observations of, and aspirations for their ancestral land (Smith, 2012). It is therefore suggested that such lopsided cross-cultural power relations embedded in research practices should be redressed by utilising decolonising research methodologies (Smith 2012). Such methodologies should be centred on locally based interests driven by an ethos of mutual benefit for Indigenous land owners and institutional researchers. As such this study, has been formulated with a sensitivity to the locally situated basis (Suchet, 2002) and contextual relevance of IEK in synergy with the quantitative strength of Western science (McAllister, 2014), all in congruence with a two-way (Ens, 2012) or eco-cultural (Harris & Harper, 2000) research approach. While the majority of the research conducted for this thesis took place in 2016 (see methods), preliminary meetings with TOs and researchers occurred during 2015. In contrast with typical research approaches in which research questions arise from scientific literature, the aim of this preliminary phase was to explore locally meaningful research questions with import for local Indigenous land and sea management. Through consultations with TOs it became clear that coastal *Melaleuca* spp. (paperbark) dieback was an emerging and significant ecological and cultural (eco-cultural) issue in the Laynhapuy IPA. Key outcomes of these initial consultations related to *Melaleuca* dieback are presented in the following section.

## 1.3 Traditional Owner observations of *Melaleuca* spp. dieback on coastal floodplains of the Laynhapuy IPA

In north-east (NE) Arnhem Land in the Northern Territory (NT), Yolŋu TOs from the Laynhapuy IPA (Figure 1 - labelled number 21; Figure 4) recently expressed concern about the death of *Melaleuca* spp. (paperbark) stands at several different sites along floodplain margins (E. J. Ens, 2015 pers. comm.; D. Guyula, 2015 pers. comm.; J. Wunungmurra, 2015b pers. comm; Figure 2). Prompted by this concern, the research presented in this thesis investigated the potential drivers of *Melaleuca* spp. dieback to inform future management. A collaborative eco-cultural research approach was adopted to deploy on-ground local Aboriginal and Western scientific assessments of the likely factors implicated in the observed dieback. Importantly, as this was an eco-cultural study, *Melaleuca* dieback affected sites and especially the likely causal factors were discussed with senior Traditional Owners who had the authority to speak for each site.

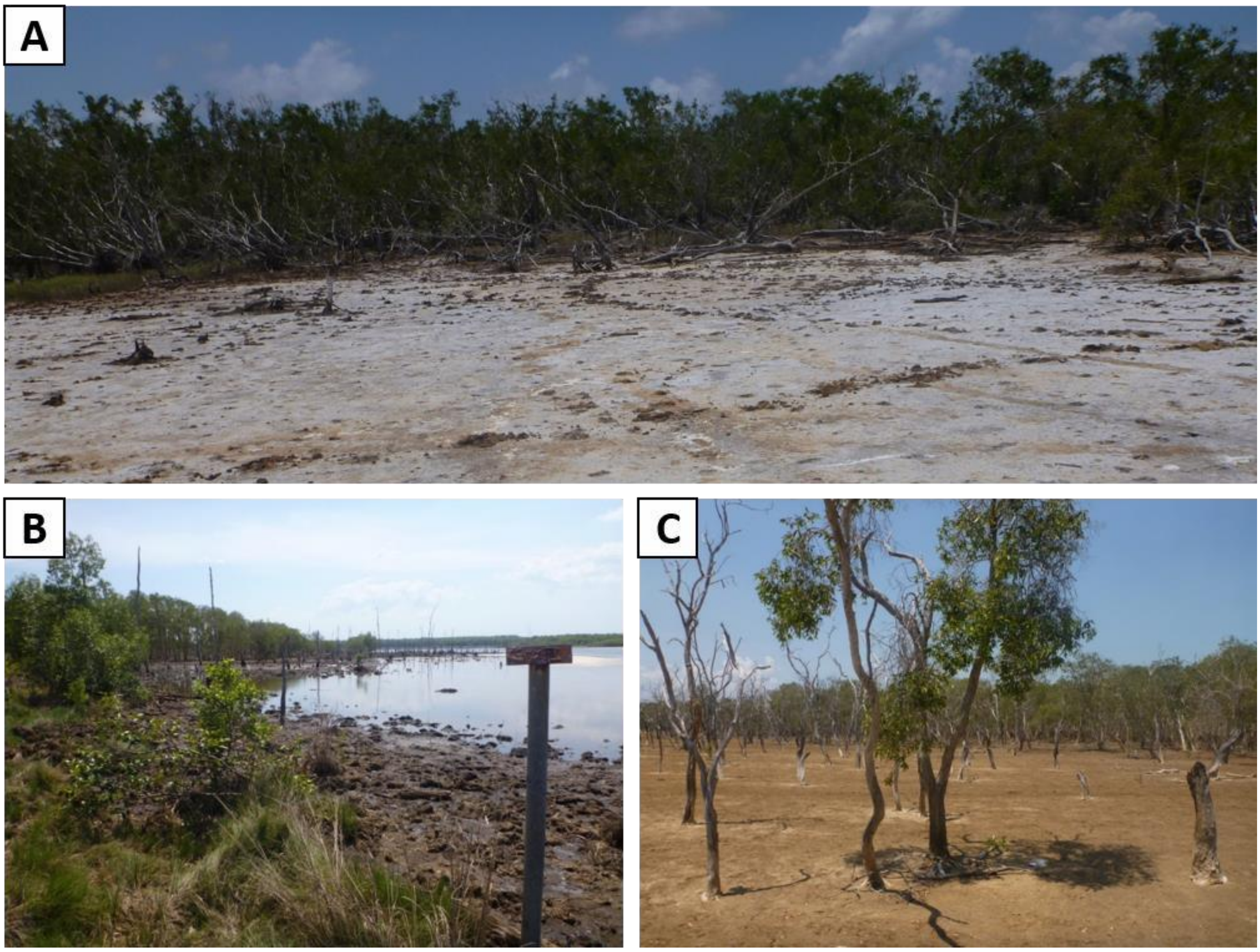


**Figure 2 -** *Melaleuca* spp. dieback at coastal floodplains of Laynhapuy IPA, NE Arnhem Land, 2015. (A) Buymarr floodplain. Dead *Melaleuca acacioides* leaning over, possibly due to a cyclone. Healthy *M. acacioides* can be seen behind them. A salt crust is also noticeable on the ground surface. Photo: D.R. Sloane. (B) Gurrumuru floodplain. The dead *Melaleuca cajuputi* can be seen standing with no foliage. A healthy patch of *M. cajuputi* remain at the back left of the image. Slightly left of centre mangroves (*Avicennia marina*) can be seen. In the foreground, feral pigs have uprooted vegetation leaving disturbed soil behind. Photo: E.J. Ens. (C) Balma floodplain (Mangayak). The stark contrast between the dead *Melaleuca* area (centre) and the live *Melaleuca* area (right) is apparent. To the left of the image (off camera) is an ocean connected stream. Photo: D.R. Sloane.

## 1.4 Indigenous relationships to Country and *Melaleuca* species in north-east Arnhem Land

The world over, Indigenous peoples identify with species and sites of particular importance, by virtue of their necessity as food resources, medicine, for materials or as totems, for example, those who call themselves the 'people of the deer' in Canada (Garibaldi & Turner, 2004). Indigenous people identifying with places and species can be personally affected when those places, species or cultural knowledge associated with them are lost. For example, in British Columbia negative impacts on the health of Indigenous people have been observed due to changes in diet from losses of cultural knowledge associated with traditional food plants (Parish *et al.* 2007). Furthermore, changes in accessibility of regions with particular species of cultural significance can inhibit traditional practices and change peoples' association with places (Turner & Turner, 2008). This was highlighted in British Columbia (1914) when Chief Cesaholis addressed the Royal Commission on Indian Affairs (British Columbia). He expressed his concern over the way in which fences being constructed by Whiteman in the estuary of the Kingcome River, were impeding Indigenous women from harvesting food in the ways they had traditionally done for many years (Turner & Turner, 2008).

In Australia, similar relationships between Aboriginal people and their ancestral lands have been documented. Relationships to plants and animals are important for emotional, social and physical wellbeing of Aboriginal people (Kingsley *et al.* 2010). For example, the physical activity associated with collection of bushfoods and the superior nutrition of bushfoods when compared with Western diets has led to documented health benefits for Aboriginal people in the 'Top End' (northern NT) (Garnett & Sithole, 2007). In NE Arnhem Land, aspects of the cultural importance of *Melaleuca* can be found in ethnobotany publications. The range of culturally important uses of *Melaleuca* for north-Australian Aboriginal people, including Yolŋu people, is significant. One such important use is as bush medicine. For example, crushed leaves of *Melaleuca cajuputi, M. leucadendra, M. acacioides* or *M. viridiflora* can be placed in hot water and the resulting steam is inhaled to treat coughs, colds and nasal congestion. Alternatively, a wash made from the leaves and water can be applied topically to the area of irritation (Cowie *et al.* 2000; Yunupiŋu *et al.*, 1995; Wrigley & Fagg, 1993; Aboriginal Communities of the Northern Territory of Australia, 1988; Levitt, 1981). In addition, there are several other uses of *Melaleuca* parts by Aboriginal people in the Northern Territory; some of which are outlined in Table 1.

**Table 1** - Some Aboriginal uses for *Melaleuca* spp. in the Northern Territory (Yunupiŋu *et al.* 1995; Wrigley & Fagg, 1993; Aboriginal Communities of the Northern Territory of Australia, 1988; Smith, 1987; Levitt, 1981). Shaded cells indicate species uses. Scientific and Yolŋu names (primarily from Rirratjiŋu - a dialect of the Dhaŋu language) of plants and the moieties to which the names belong (i.e. Dhuwa or Yirritja) are listed. Language names are based on Zorc *et al.* (2014) and Yunupiŋu *et al.* (1995). See appendix 1 for more Yolŋu names for *Melaleuca* spp.

| **Aboriginal resource uses** | ***M. acacioides*** Gulun'kulun (Dhuwa, Yirritja) | ***M. cajuputi*** *Nhami* (Dhuwa) *Raŋan* (Yirritja) | ***M. dealbata*** Nämbarra (Dhuwa) | ***M. viridiflora*** *Dindin* (Dhuwa) *Rakala* (Yirritja) |
|---|---|---|---|---|
| **Leaves crushed and inhaled to treat colds and coughs** | ■ | ■ | ■ | ■ |
| **Leaves used to make liniment for chest congestion, body pains** | ■ | ■ | | ■ |
| **Leaves and water make a remedial drink for coughs and colds** | | ■ | | ■ |
| **Bark used to wrap bodies for burial** | | ■ | | |
| **Bark used to carry babies** | | ■ | | |
| **Bark used to make coolamons (containers)** | | ■ | ■ | |
| **Bark used for blankets** | | ■ | | |
| **Wood used to make canoes** | | ■ | | ■ |
| **Water from swellings in the tree can be drunk** | | ■ | ■ | ■ |
| **Leaves used to flavour meat or seafood** | ■ | | | |
| **Bark used as clothes for women** | | | | ■ |
| **Leaves are a mosquito repellent when burned** | ■ | | | |
| **Bark used in rain shelters** | | | ■ | ■ |
| **Flowers indicate good turtle hunting** | | | | ■ |

In NE Arnhem Land, it may be difficult for future Yolŋu to maintain a culturally (and ecologically) significant relationship with *Melaleuca* forest and species at the places they have historically existed if they no longer occur there. Further enquiry into the causes of *Melaleuca* dieback is therefore based on TO concerns for the longevity of these culturally significant species, ecological curiosity and assessing potential threats to inform management. Accordingly, the following sections of the introduction of this thesis will examine broader theories of tree dieback which were used to guide the ecological analysis and interpretation of *Melaleuca* dieback in the present study.

## 1.5 Potential causes of tree dieback

Tree dieback refers to the death of trees and can be observed at as "standing snags" (dead trees) or "still-living but stag-headed trees" (partially dead trees) (Mueller-Dombois, 1986). Rather than dieback of individual trees, the causes of which may be 'natural' and stochastic, this thesis is particularly concerned with stand-level dieback. This involves entire stands of trees dying rather than isolated death(s) of individuals (Mueller-Dombois, 1988; 1986). Typically, during dieback events, large numbers of trees die in near synchrony with a loss of foliage usually beginning from the top of the tree and moving downward (Mueller-Dombois, 1986).

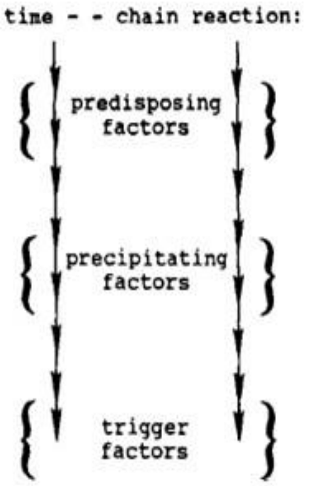


**Figure 3** - Chain reaction of causal factors contributing to stand-level dieback. Adapted from: Mueller-Dombois (1988).

Often a multitude of factors combine to produce stand dieback (Ross & Brack, 2015; Landsberg & Wylie, 1988; Mueller-Dombois, 1988; Wylie, 1986). Chain reaction theory (Mueller-Dombois, 1988) provides a framework from which the causes of stand-level dieback can be conceptualised as a chain reaction, rather than attempting to identify a single cause. Accordingly, the chain reaction of causal factors can be understood in terms of predisposing, precipitating and trigger factors (Mueller-Dombois, 1988; Figure 3).

Predisposing factors of stand-level dieback can be related to stand demography or edaphic factors that may dictate a predisposition to stand death (predisposing in Figure 3). These can include both endogenous and exogenous factors (Mueller-Dombois, 1988). Typically, predisposing factors occur in a 'press' fashion i.e. they will be endured and adapted to by trees over long time periods (Mac Nally *et al.* 2014). Precipitating factors contribute to tree decline and dieback over time, again typically in a press fashion. In the NT, potential precipitating factors (precipitating in Figure 3) have been documented as present and past land uses (e.g. buffalo occupation) or saltwater intrusion (Bowman *et al.* 2010; Steffan *et al.* 2009; Mulrennan & Woodroffe, 1998; Finlayson *et al.* 1997). Trigger factors are perturbations that occur in a sudden 'pulse' fashion (Mac Nally *et al.* 2014; trigger in Figure 3). These could be hypothesised as perturbations such as abrupt pest incursion or extreme weather events, although neither of these factors have been explored in *Melaleuca* stands of northern Australia.

Deployment of Mueller-Dombois' chain reaction theory therefore requires a detailed assessment of likely predisposing, precipitating and trigger factors.

### 1.5.1 Predisposing factors

Stand structure is considered of key importance to stand-level dieback (Mueller-Dombois, 1988). For *Melaleuca* in NE Arnhem Land, the stand demography can be assessed by studying the stand size/age structure. Measurements of stand structure may include analyses of tree ages, sizes, canopy cover or density (Mueller- Dombois, 1988). An inverse J-curve with high juvenile recruitment followed by natural thinning of the stand (Girma & Mosandl, 2012; Ens & French, 2008; Omeja *et al.* 2004) to "carrying capacity" (Zeide, 2001; Smith *et al.* 1997) is typical of healthy and regenerating tree stands. As plants in a cohort age, the number of survivors decrease over time (Harper, 1967; Sagar, 1959) and the risk of mortality of individual plants can increase significantly with age (Sarukhan & Harper, 1973). Pursuant to the phenomena of stand-level dieback, it follows that if trees in a stand are all of the same age, over time their predisposition to senescence will increase to a point when they may all begin to die around the same time, especially if a death-trigger event occurs during such vulnerability (Mueller-Dombois, 1988). In order to understand possible causes of plant dieback generally, and *Melaleuca* dieback specifically, it is critical to understand trends in recent recruitment (Tilman, 1997). This is because recruitment limitation is likely to be an important determinant of community structure and native plant population change (Yates & Broadhurst, 2002).

Edaphic (soil) and habitat conditions (especially ecotone dynamism at coastal floodplain fringes) could be considered as predisposing factors for stand level dieback. The dynamic floodplain fringe ecotone that occurs at the interface of fresh and saltwater environments is subject to seasonally variable temperature, moisture and salinity, exemplified by wet season high tides (Cowie *et al.* 2000). There are seven species of *Melaleuca* in NE Arnhem Land (Atlas of Living Australia, 2016), which vary in terms of their salinity, inundation and pH tolerance and their habitat preferences (Table 2). In general, the biogeography of different *Melaleuca* species corresponds to each species' tolerance to local flooding, and salinity (Cowie *et al.* 2000). Additionally, *Melaleuca* are often tolerant of variable soil and water pH as this also fluctuates seasonally. pH reaches its lowest values in the dry season, typically as low as 3.5 pH units (Cowie *et al.* 2000). Coastal floodplains in NE Arnhem Land (and much of Australia) are considered as being potential or in some cases actual acid sulfate soils (Worley-Parsons, 2013; Willet, 2008). This may be relevant for understanding tree dieback in NE Arnhem land, and other places where these soils occur, as acid sulfate soils are known to negatively impact vegetation (Ahearn *et al.* 1998; Inraratna *et al.* 1995). In the Northern Territory, some research has been conducted on acid sulfate soils in the vicinity of Kakadu National Park (see review by Willet, 2008), but no fieldwork has been conducted in NE Arnhem Land. A recent desktop study revealed a potential acid sulfate soil risk of the Laynhapuy floodplains (Worley-Parsons, 2013). Considering the edaphic and habitat characteristics of *Melaleuca* in NE Arnhem Land, a number of related precipitating factors may generate new and exacerbate existing conditions that could threaten the viability of coastal floodplain stands.

**Table 2 –** *Melaleuca* species with observed dieback in NE Arnhem Land and their ecological tolerances. References are numbered with citations listed at the foot of the table.

| *Melaleuca* species | Salinity tolerance | Soil types | pH tolerance range | Habitat |
|---|---|---|---|---|
| ***Melaleuca viridiflora*** **'Broad-leaved paperbark'** | Prefers partial freshwater inundation from a high water table or surface water in wet season [1] | Acid organic sands and loams, lateritic flats, red gravels and edges of black soil [1,2] | 5.4-9 [9] | Often forms monospecific stands in coastal marshes, swamps, estuarine plains [1] hillsides in forest to heath. |
| ***Melaleuca acacioides*** **'Coastal paperbark'** | A salt tolerant species [2,3] | Sandy soils [8] | ?-8 [10] | Mudflats edges, river banks, periodically inundated saline depressions on the landward side of mangroves [5] |
| ***Melaleuca cajuputi*** **'Cajuput'** | A mildly salt tolerant species [3] | Sandy loam, loam and clay soils on coastal plains and seasonal swamps [3]. Cracking black clay, black peaty sand, and clay loam [2]. Also acid sulfate soils [6] | 3.3-6.65 [6,7] | Often forms monospecific stands in swamps or can be found as a stunted growth form on coastal dunes [3] |

References, 1: (Boland *et al.* 1986), 2: (Brophy *et al.* 2013), 3: (Wrigley & Fagg, 1993), 5: (Levitt, 1981), 6: (Osaki *et al.* 1998), 7:(Nguyen *et al.* 2003), 8: (Barlow, 1987), 9: (Jones, 1997), 10: (Hamilton & Eugene, 1990).

### 1.5.2 Precipitating factors

Potential precipitating factors affecting *Melaleuca* spp. in NE Arnhem Land that can be gleaned from the literature include saltwater intrusion and feral ungulate damage. While there is a paucity of research on the local causes and impacts of saltwater intrusion in NE Arnhem Land, impacts of these factors on *Melaleuca* have been recorded in the Kakadu area, especially the Alligator and Mary River regions; east of Darwin. In these areas, significant saltwater intrusion into freshwater wetlands has been observed since at least 1950 and there is broad consensus through comparison of aerial photographs and field studies that this has mainly resulted from the landward extension of tidal creeks (Winn *et al.* 2006; Mulrennan & Woodroffe, 1998; Cobb, 1997; Knighton *et al.* 1992; Fogarty, 1982; Stocker, 1970). The Alligator and Mary River regions are coastal and consist of seasonally inundated floodplains and associated estuarine and freshwater wetlands (Finlayson, 1995; Knighton *et al.* 1992) much of which is dominated by *Melaleuca* species (Knighton *et al.* 1992). Due to the similarities to Laynhapuy IPA of NE Arnhem Land in latitude, terrain types such as coastal floodplains, ecology including the prevalence of *Melaleuca* species and the presence of buffalo, it is likely that some meaningful comparisons can be drawn.

In the Kakadu region, saltwater intrusion has been implicated in *Melaleuca* spp. dieback at the Mary River (Cobb, 1997; Knighton *et al.* 1992; Stocker, 1970), South Alligator River (Cobb, 1997; Woodroffe *et al.* 1986;

O'Neil, 1983; Fogarty, 1982), East Alligator River (Cobb, 1997; Williams, 1984), Finniss River and the Reynolds River (Fogarty, 1982). Despite these observations, it is critical to note that most of these studies have typically involved remote sensing and mapping the extent of saltwater intrusion, using the observed extent of *Melaleuca* spp. dieback as an indicator of this phenomenon. As such it appears that assumptions have been made regarding the association of *Melaleuca* spp. dieback and saltwater intrusion *a priori.* Although, at Point Farewell, the mouth of the East Alligator River, Cobb (1997) did find higher levels of electrical conductivity of soil/water mixtures at a site of *Melaleuca* spp. dieback (6.19 mS/cm) compared to a healthy *Melaleuca* spp. forest site (1.19 mS/cm). Additionally, halophytic mangroves were observed encroaching on saltwater intrusion sites. These findings are congruous with findings by Stocker (1970) at the Mary River floodplain, where soil sodium gradually increased in tandem with *Melaleuca* spp. sickness. While the trend appears to exist in northern shores of the Top End of the NT, verification in the Gulf of Carpentaria is required.

*Melaleuca* spp. of the present study are known to demonstrate salinity tolerance, albeit to different degrees (Table 2). However, considering global sea level rise, coastal soil salinity change may be a precipitating factor affecting *Melaleuca* spp. dieback, especially for those species that require periods of freshwater inundation or drying. Sea level in the Gulf of Carpentaria is rising at one of the fastest rates in Australia, at about 10-11mm yr-1 since 1993. This is around 3 times the global average of ~3.4mm/yr-1 (White *et al.* 2014; Figure 4). Among numerous positive feedback mechanisms, this higher rate of sea level rise appears to be due to warming sea temperatures resulting in thermal expansion of water, causing low pressure systems, correlated with ENSO phenomena (White *et al.* 2014). This may partly explain accelerating rate of saltwater intrusion in

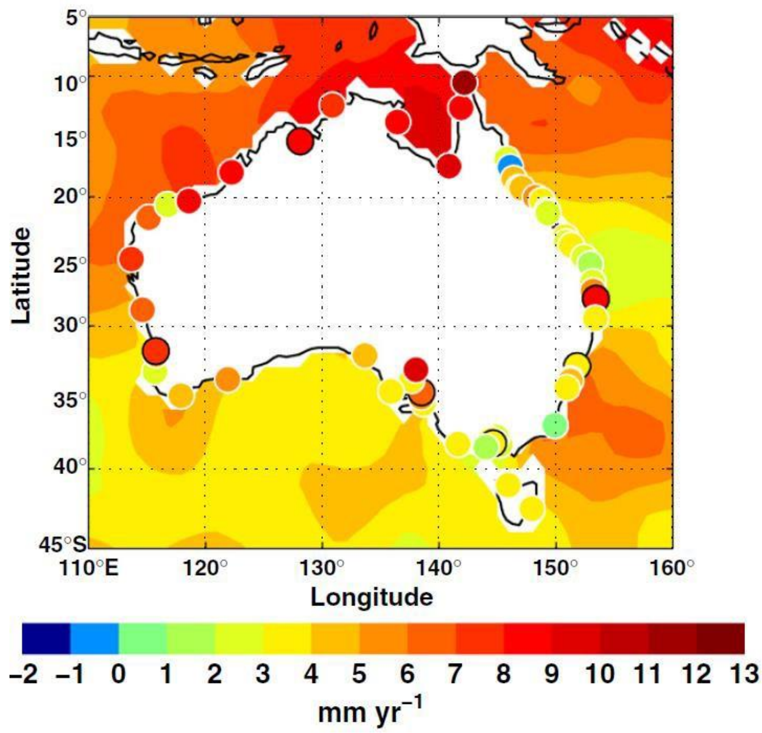


**Figure 4** – Regional sea level rise around Australia from 1993-2010, based on tide gauge (coloured dots) and satellite altimeter data (coloured contours). Colours of ocean and tide gauges mainly grade from yellow (moderate sea level rise) to red (extreme sea level rise). Note the anomalously high rate of rise on the north coast, especially the Gulf of Carpentaria. Source: White *et al.* (2014).

the Northern Territory since at least the 1980's (Steffan *et al.* 2009), however it has been suggested that this may be difficult to disentangle from natural system variability and the effects of buffalo swim channels driving saltwater intrusion in the region (Cobb *et al.* 2007).

While *Melaleuca* are generally tolerant of waterlogging (in many cases waterlogging even stimulates growth), Van der Moezel *et al.* (1991) demonstrated that *M. viridiflora* and *M. leucadendra* seedlings grown in laboratory conditions exhibited reduced survival in a saltwater-logged treatment when compared with freshwater grown treatments. In northern Australia, the combination effect of waterlogging and salinity, as is expected from sea level rise, may be especially detrimental to these two *Melaleuca* species (Van der Moezel *et al.* 1991). Although this study was limited to Melaleuca grown from seed and thus does not address the tolerance of established, adult plants, analysis of pollen in soil cores and radiocarbon dating indicates that *Melaleuca* forest and mangrove salt marsh have oscillated in their ranges over many thousands of years before present, primarily due to changes in sea level (Cowie *et al.* 2000; Woodroffe *et al.* 1985).

Biotic agents can also contribute to precipitous tree decline and/or provide the final death blow to tree stands that are already dying (Mueller-Dombois, 1988). Feral ungulates have the capacity to act as biotic agents creating disturbances to vegetation and the morphology of rivers and floodplains (McKnight, 1971). In NE Arnhem Land feral ungulates primarily include buffalo (*Bubalus bubalis*), pigs (*Sus scrofa*) and to a lesser extent cattle (*Bos taurus*) (Saalfield, 2014, 2006; Bayliss & Yeomans, 1989). Documented impacts of these animals include: soil compaction, vegetation damage and erosion of soil through trampling and grazing of vegetation (Ens *et al.* 2016; Bird, 2008; Petty *et al.* 2007; Skeat *et al.* 1996).

Buffalo have been implicated in a number of destructive processes that damage ecological and cultural assets, including the destruction of bushfoods such as turtles (Albrecht *et al.* 2009) and water lilies (Ens *et al.* 2016). In relation to *Melaleuca* dieback, buffalo are known to trample *Melaleuca* forest and create swim channels that drive saltwater intrusion into freshwater billabongs and floodplains (Bowman *et al.* 2010; Skeat *et al.* 1996; Fogarty, 1982; Stocker, 1970). Interestingly, from aerial photographs and on-ground observations at the Reynolds and Finniss Rivers, Fogarty (1982) found that the impact of saltwater intrusion on vegetation occurred after heavy buffalo occupation. It was reasoned that the buffalo had increased the depth of shallow channels and connected saltwater and freshwater reaches of the rivers, resulting in increased saltwater flooding. Impacts included erosion of banks, death of water lilies, and reduced condition of vegetation at the edge of increasingly salinised water bodies.

Desktop studies of Kakadu utilising historical aerial photographs have attempted to relate historical buffalo densities to woody thickness of Eucalypt dominated savanna (Bowman *et al.* 2008) and *Melaleuca* swamps (Bowman *et al.* 2010). In both cases a weak inverse correlation was found between buffalo density and woody thickness. Instead, it was suggested in the case of the northern Australian savannas, proximity to propagule sources, increased rainfall and changed fire regimes are likely to have a greater impact on woody thickening than buffalo density. However, examination of photographic and oral evidence in addition to on ground studies by Petty *et al.* (2007) have found that buffalo occupation typically results in reduced woody vegetation cover, although effects vary regionally. For example, central floodplains of the Alligator Rivers Region (dominated by *Melaleuca* spp.) experienced reductions in woody cover (Petty *et al.* 2007), whereas c.400km southeast at the Victoria Rivers Region, floodplain woody cover increased (mainly due to *Eucalyptus microtheca* and *Excoecaria parvifolia* growth) (Sharp & Whittaker, 2003).

Given the observed impacts of buffalo on wetlands and *Melaleuca* forest, the effect of large buffalo populations in the Laynhapuy IPA may be significant for *Melaleuca* spp. dieback. Estimates of buffalo populations in northern Australia have fluctuated since 1985 when aerial surveys were conducted (Bayliss & Yeomans, 1989). In large part these fluctuations have been due to eradication campaigns targeting buffalo. The most historically salient of these campaigns was the Australia wide brucellosis and tuberculosis eradication campaign (BTEC), which ran from 1970-1997 (Neumann, 1999) for the purpose of eradicating all feral and domestic bovids infected with either of the diseases (Anon, 1989). While the BTEC was effective at reducing buffalo populations in northern Australia (Lehane, 1996; Freeland & Boulton, 1990) and Australia wide (Lehane, 1996), soon after the conclusion of BTEC Buffalo populations rebounded in Arnhem Land, including in the Laynhapuy IPA, with increasing populations since 1998 (Saalfield, 2014). Since then a shift in the buffalo population centre from the Kakadu region towards Maningrida and Arnhem Land more broadly has been observed (Garnett & Sithole, 2007). The most recent population estimates in Arnhem Land by Saalfield (2014) were 97,923 ± 9,327. This equates to a density of 1.07 ± 0.1 buffalo per square kilometer. Buffalo sightings were primarily concentrated on floodplains (Saalfield, 2014), which, given the harmful ecological and cultural impacts, may pose a threat to floodplain flora such as *Melaleuca* species.

Feral pigs also pose a major threat to environmental and cultural assets in Australia including NE Arnhem Land (West, 2008). This is due to their rooting behaviour that involves digging around the base of plants to eat the roots which negatively impacts native plants themselves, the soil and the seed bank (DEH, 2005; Bowman & McDonough, 1991). Pigs creating erosion gullies (channels) has been noted by Jawoyn elders of the Kakadu region (Robinson & Wallington, 2012), suggesting that, similar to buffalo, pigs may be able to contribute to saltwater intrusion through channel effects. Pigs dig up large amounts of soil in wetlands, contributing to denudation and erosion as they search for plant tubers and corms (especially *Eleocharis* spp.), worms and turtle eggs (Kakadu National Park Board of Management, 2016; Albrecht *et al.* 2009; Garnett & Sithole, 2007). The impact on *Eleocharis* spp. is significant as this is an important food for magpie geese (Kakadu National Park Board of Management, 2016) and Aboriginal people (B. Wunungmurra, 2015a pers. comm.). They predate on several other native species including frogs, lizards and small mammals (Kakadu National Park Board of Management, 2016) and also eat grass seeds that reduce food availability for birds such as the golden-shouldered parrot (*Psephotus chrysopterygius*) (Crowley *et al.* 2004).

The harmful ecological impacts of pigs has led to listing predation, competition and disease transmission by pigs as a key threatening process under the EPBC Act (1999). The Department of the Environment (2015) listed 142 threatened species and ecological communities as adversely affected by pigs. While *Melaleuca* species are not included on this list, experiments in north-Queensland rainforest have demonstrated that pigs reduced woody seedling abundance by 37% compared to pig-excluded control sites (Mitchell *et al.* 2007). The population density of feral pigs is much harder to estimate than buffalo (Saalfield, 2014), but there are reports that feral pigs pose a significant risk to ecological and cultural assets in the Laynhapuy IPA (Ens & Kerins, 2009). For example, during 2015 preliminary consultations, a Traditional Owner in Laynhapuy IPA suspected that pig digging around *Melaleuca* spp. roots may be increasing saltwater infiltration to the detriment of tree health (J. Wunungmurra, 2015b). For these reasons pigs are suspected to be a precipitating factor contributing to decline and dieback of *Melaleuca* spp. at Laynhapuy IPA and must therefore be investigated.

## 1.6 Research questions and aims

This chapter reviewed the literature related to Indigenous land and sea management, cross-cultural collaborative research approaches, Aboriginal significance of *Melaleuca* species and possible causes of tree dieback; especially as relevant to *Melaleuca* species present in Laynhapuy IPA. Through critical review of the literature it is clear that the causes of tree dieback may be complex and include multiple factors. It is also clear that on Aboriginal owned land, a research methodology that is driven by, beholden to and inclusive of local Aboriginal people is required in order to drive locally meaningful research processes and outcomes. The primary aim of this thesis is therefore to deliver an eco-cultural understanding of *Melaleuca* dieback in the Laynhapuy IPA through applied eco-cultural research. This approach aims to embody a strong cross-cultural and collaborative ethos throughout by exploring the inextricable socio-cultural and ecological elements of *Melaleuca* dieback on Aboriginal land. Using mixed eco-cultural research methods this thesis will answer the following research questions:

1. What do local Yolŋu traditional owners (TOs) think is causing *Melaleuca* spp. dieback?
2. Are there clearly definable areas of “alive” and “dead” *Melaleuca* spp.?
3. Do “alive” and “dead” *Melaleuca* spp. stands differ in health between different height classes?
4. Are actual or potential acid sulfate soils present at the study sites?
5. Which ecological factors are the best predictors of *Melaleuca* spp. dieback?
6. Are there advantages to using eco-cultural methods?

# 2 Methods

## 2.1 Study sites

The fieldwork for this research was conducted within the Laynhapuy IPA, NE Arnhem Land, Northern Territory, Australia (Figure 5). Laynhapuy IPA Stage 1 represents the current extent of the IPA that was declared in September 2006 (Department of the Environment, 2013). Stage 2, currently under consultation, is slated to extend the IPA in the future. The study sites visited for this research were coastal floodplain margins associated with different Yolŋu homelands. The five study sites utilised were places that TOs had identified *Melaleuca* spp. dieback and where there was local interest in better understanding the causes. The study sites were located at: Gurrumuru, Raymangirr, Dhuruputjpi, Buymarr and Bayapula (Figure 5). The fieldwork was conducted in the early dry season of the Australian monsoonal tropics in May 2016.

Like most of northern Australia, Laynhapuy IPA experiences a monsoonal climate, with a wet/dry season dichotomy throughout the year (Cowie *et al.* 2000). The wet season occurs from October to April, whilst the dry season occurs from May to September (The Australian Bureau of Meteorology, 2016a), although April-May and September-November may be considered transition months (Taylor & Tulloch, 1985). Annual mean minimum and mean maximum temperatures are 22.4°C and 30.7°C. Annual mean rainfall is 1468.1mm with dry and wet season variability throughout the year. As such, mean monthly minimum and mean monthly maximum rainfall is 5.3mm (August) and 281mm (February) (The Australian Bureau of Meteorology, 2016b; Figure 6).

Yolŋu people divide the year into seven seasons. Midawarr occurs from March-April and is when the dragonflies swarm and the mullets are fat. Dharratharra occurs in the cool months from May-August when the *Melaleuca* spp. flower and the flatback turtles lay eggs. Rarranhdharr occurs in the hot and dry months of September-October when the *Acacia* spp. flower and the barramundi are fat. Dhuludur occurs during October and is considered the true spring time when *Brachychiton* spp. flower and oysters are fat. Lungurrma occurs during November and is a windy month when stingrays are fat. Wolmaya occurs during the build up to rains in December when magpie geese and kingfish are fat. Bulunuya occurs in January-February when the tern eggs are ready to eat (Wettenhall & Preece, 2016).

The floodplain study sites are seasonally inundated and thus the flora conspicuously present varies throughout the year. In terms of vegetation, the greatest seasonal variation occurs in the herbaceous ground covers which are ubiquitous on the floodplains during the wet season and visually absent during the dry season (Cowie *et al.* 2000). At the floodplain study sites, there were variations in the *Melaleuca* species encountered. Gurrumuru was dominated by *Melaleuca cajuputi* which was locally referred to as raŋan. Raymangirr was dominated by *Melaleuca viridiflora* which was locally referred to as nambarra. At Dhuruputjpi *M. viridiflora* and *M. cajuputi* both occurred. Buymarr and Bayapula were dominated by *Melaleuca acacioides* which was locally referred to as gulun' kulun.

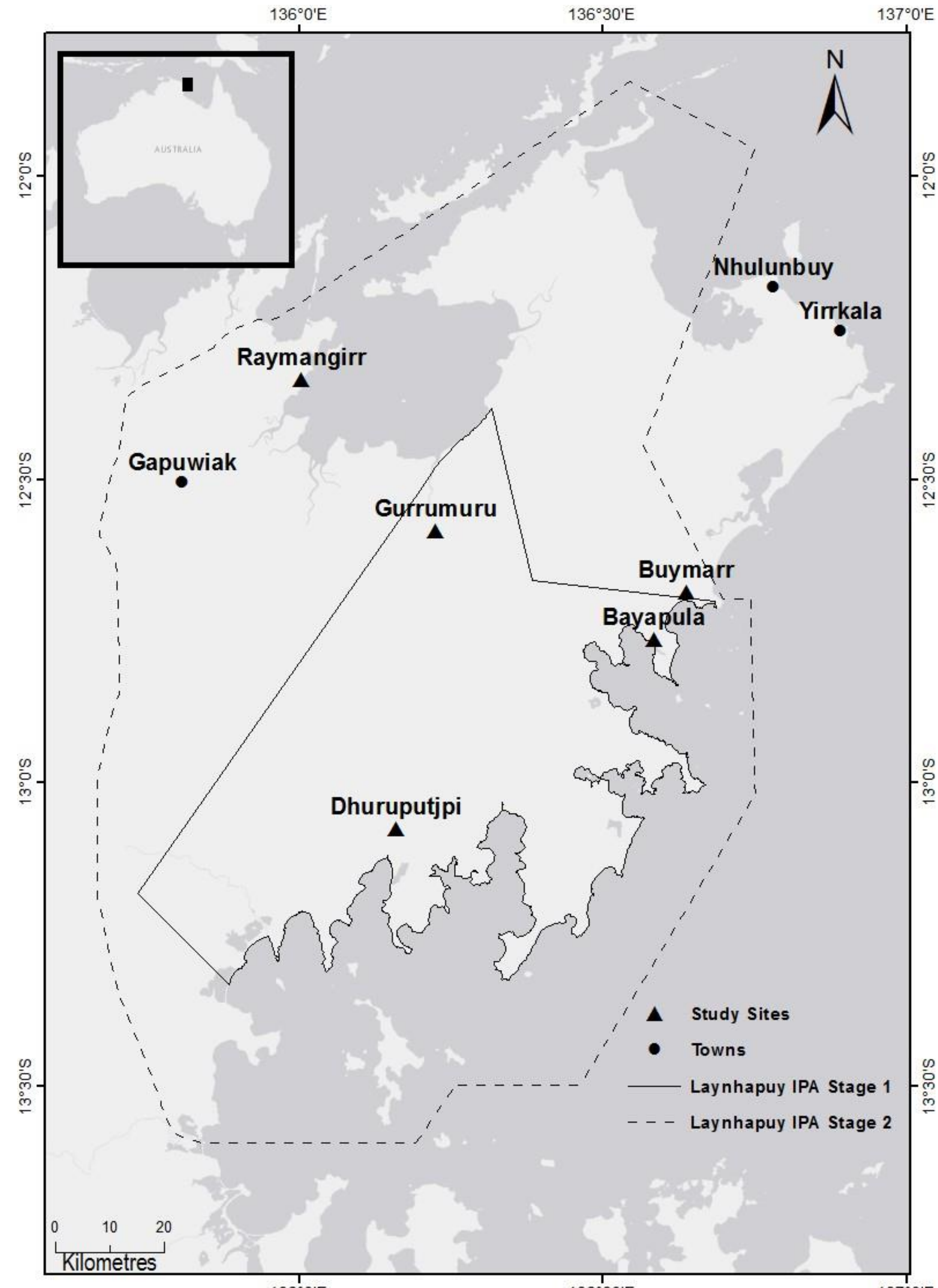


**Figure 5 -** Laynhapuy Indigenous Protected Area (IPA). IPA current extent - Stage 1 (solid line). Consultation area - Stage 2 (dashed line). Study sites (triangles). Regional towns (dots) included for reference. Map produced by the author using ArcMap v. 10.3.1 (ESRI).

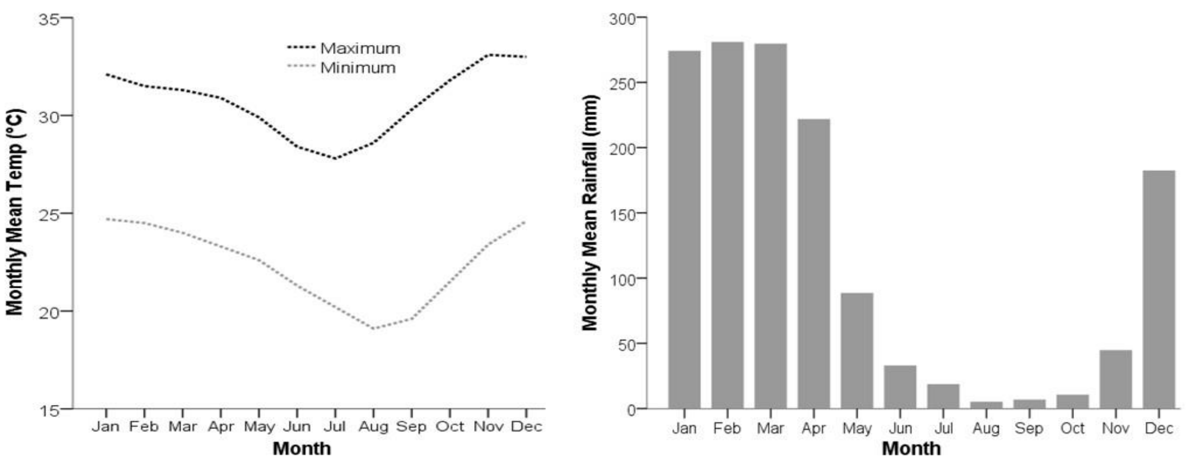


**Figure 6 -** Monthly mean maximum and minimum temperature (°C) and monthly mean rainfall (mm). Data was collected at Gove (Nhulunbuy) airport between 1966 and 2016. Data source: The Australian Bureau of Meteorology (2016b).

## 2.2 Elicitation of socio-cultural knowledge of *Melaleuca*

Initial consultations with key TOs about the cultural significance and explanations of *Melaleuca* spp. dieback on their ancestral clan estates (Homelands) were conducted in September 2015 under the guidance of the Yirralka Rangers who are tasked to manage the Laynhapuy IPA. The intent of these consultations was to meet up with TOs and discuss their observations of *Melaleuca* spp. dieback and gauge interest in establishing a collaborative cross-cultural research project (see Smith, 2012). Some of the key outcomes of this preliminary phase have been presented in section 1.2.

Following granting of permissions and permits (Northern Territory Government and Northern Land Council permits), field work was conducted in May 2016 to further understand the cultural significance and local TO perceptions of *Melaleuca* dieback. These consultations took the form of semi-structured interviews containing open-ended questions with locally meaningful wording. The focus was on question wording that did not contain answers that could be perceived as being desired by the researcher. This was in order to attain accurate accounts from interviewees (Breuer *et al.* 2002). The semi-structured nature of the interviews meant that questions stimulated rather than prescribed discussion. This enabled interviewees to navigate the conversations in a culturally appropriate manner. This is a similar method to that used by Petheram *et al.* (2010) and Zander *et al.* (2013) who previously conducted social research about environmental change in this region.

Knowledge in Indigenous societies is complex. For example, who is culturally allowed to share different types of information is regulated by Aboriginal Law (Morphy, 2008). Petheram *et al.* (2010) have also noted that the social status of participants can influence the depth of responses. As such, senior TOs were identified by the Yirralka Rangers for each of the study sites and interviewed as they were likely to have a high level of knowledge regarding their land and an acute awareness of what they were allowed to share. This collaborative approach of working with Yolŋu Rangers to identify research participants ensured that the right people were being consulted for the right places. Yirralka Rangers were highly informed regarding the aims and collaborative nature of this project and were therefore able to communicate this to TOs in a culturally appropriate manner and through the use of local Yolŋu matha languages. In this way, all TOs understood the purpose of the project and were able to make an informed decision regarding their participation.

During semi-structured interviews, TOs had the freedom to talk about ecologically and culturally significant issues and to share knowledge related to *Melaleuca* dieback on their land. In particular, TOs were encouraged to discuss their views regarding possible causes of the dieback. They had the option of speaking in English or traditional Yolŋu matha languages. These interviews were recorded in audio-visual format, subject to TO's consent (according to the Macquarie University Human Research Ethics agreement, reference number 5201500755; appendix 2). Interviews spoken in Yolŋu matha were translated into English by Gurrundul Marika; native Yolŋu matha speaker and Yirralka Miyalk (women) Rangers facilitator. Interview questions that were used as a basis for these discussions were as follows:

### 2.2.1 Semi-structured interview questions

Identifier and Authority questions:

1. What is your name?
2. How old are you?
3. Is this your Country?
4. Are you allowed to speak for this Country?
5. What is this place called? Does it have a name?

Familiarity questions:

6. How often do you come here?
7. Why do you come here?
8. Do you come in a particular season or time of year? If so when?
9. When was the first time you came here?
10. Who brought you here the first time?

Questions about observed change:

11. Have you noticed any changes at this floodplain?
12. If so, when did you notice the changes?
13. Why do you think these things changed?

If *Melaleuca* spp. were not mentioned, a more directed question was asked:

14. Have you noticed any changes in the paperbark trees?

Then there was an opportunity for any comments that TOs wished to add:

15. Is there anything else you think might be happening here?
16. Is there anyone else you think we should talk to about this are?

## 2.3 Ecological study design

At each of the five study sites, two quadrats were purposively selected in collaboration with the Yirralka Rangers to represent "alive" and "dead" areas (five study sites x two quadrat types at each = 10 quadrats total). Quadrat sizes of 20 x 20m (400 square metres) were used as this has been found to be ample for *Melaleuca* surveys across a range of factors (Crowley *et al.* 2009; Brocklehurst & Van Kerckhof, 1994). Areas of dieback were surveyed alongside alive *Melaleuca* spp. stands, allowing direct comparisons (see Ross & Brack, 2015) akin to control-impact studies. In each quadrat, systematic ecological measurements were taken along five parallel 20m transects (using a point transect method at each 1m) and 3 soil sample points were used according to the sampling schema (Figure 7).

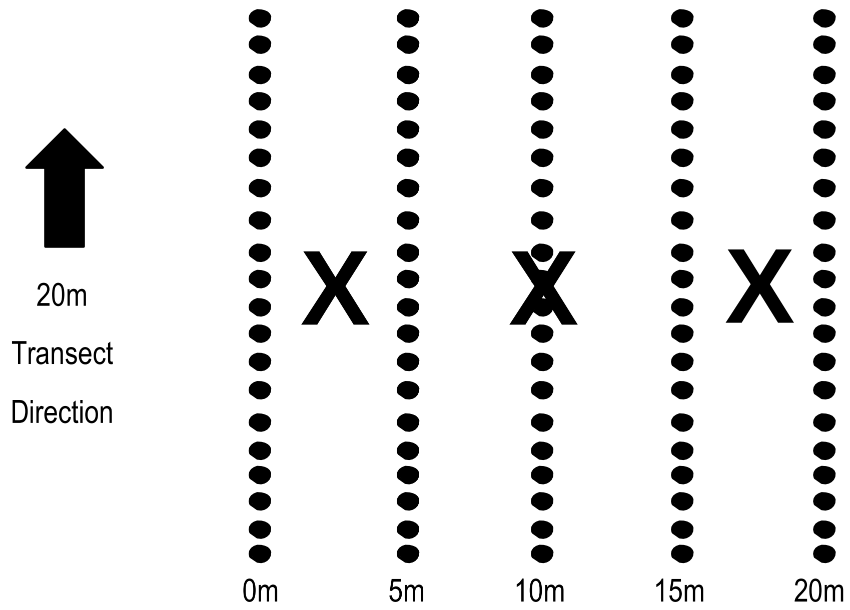


**Figure 7 -** Quadrat schema. Five point transects began from the 0m mark and were performed every 5m after that. At each 1m along each transect (black dots) a series of observations were recorded using the point transect method. The X's denote the soil sampling locations within each quadrat. Soil was sampled at 10 cm and 50 cm depths in the soil profile.

Transect data was collected electronically using a CyberTracker® application uploaded onto a handheld computer in a fashion similar to Ens *et al.* (2010). Every one metre point along each transect (100 points in total), the ground moisture, surface feature and ground cover feature was recorded as well as canopy cover. Responses for each category were pre-determined and provided in the CyberTracker® application as single choice "answers". The responses for ground moisture were: wet, moist or dry. The responses for ground surface features were: pig damage (tracks or digging), buffalo damage (wallow, pad or pug), flat ground, or disturbed ground. The ground cover feature options were: bare ground, leaf litter, dead wood, water, grass or tree. Overhead canopy cover was recorded as present or absent using a canopy densitometer (cf. canopy closure: Fiala *et al.* 2006; Korhonen *et al.* 2006).

*Melaleuca* species in each quadrat were identified using Yolŋu and Western scientific approaches. Within each quadrat, again using a pre-constructed CyberTracker® electronic data collection application, *Melaleuca* stems were counted and their health assessed as being either healthy (full canopy), sick (partial canopy) or dead (no canopy). Data collectors also recorded each tree heights using the following categories: <1m, 1-2m, 2-5m, 5-10m or >10m.

Soil was sampled at three points in each quadrat (Figure 5) at both 10 cm and 50 cm depths (i.e. 6 samples per quadrat). Soil water was squeezed out of the soil by hand as much as possible before 5g of soil was mixed with 25 mL of demineralised water (i.e. soil: water ratio of 1:5 as per Rayment & Lyons, 2011). To assess the presence of actual or potential acid sulfate soils $pH_w$ was measured immediately and recorded every 30 seconds for 3 minutes (measures oxidation of any sulfides to form sulfuric acid). $pH_w$ was measured using a PCSTestr 35 (©Thermo scientific) electronic meter, accurate to ±0.01 pH units. Simultaneously, a separate soil water mixture (1:5) was mixed for 3 minutes by vigorous shaking. From the latter mixture $EC_{1:5}$ and sodium chloride

(NaCl) was then measured using a Eutech Cond 610 (© Thermo scientific), accurate to ±1%. Both pH and salinity measurements were automatically temperature compensated to 25°C as per Rayment & Lyons (2011).

Prior to going into the field an acid sulfate risk map was developed using data from the Australian soils resource information system (ASRIS). As little ground truthing work had been undertaken in NE Arnhem Land, data were based upon theoretical expectations of the likelihood of acid sulfate soils based on terrain and soil type. Geospatial distribution of acid sulfate soil likelihood was mapped using ArcMap v. 10.3.1 (ESRI).

## 2.4 Data analysis

### 2.4.1 Socio-cultural data

Computer-assisted qualitative data analysis software NVivo v11 (QSR International, 2015) was used to analyse interview data. NVivo was used to code interview responses (data) into themes (nodes) regarding the cultural significance of *Melaleuca,* observed changes in *Melaleuca* over time, suspected causes of these changes and any other knowledge that arose. This analytical coding technique followed a thematic analysis methodology which allowed themes to emerge from the data, rather than forcing data into pre-ordained themes as is common with other coding methods (Saldaña, 2013). A similar approach has been used in social studies used to support improved Indigenous access to their ancestral lands in Victoria, Australia (Kingsley *et al.* 2008). Thematic analysis allowed answers to emerge organically from TO responses to questions regarding the locally perceived causes of *Melaleuca* dieback, with the added benefit of integrating other eco-culturally salient information that Western researchers may not have understood as being relevant *a priori.* Doing so was considered important in order to uphold the decolonising research principle of methodological flexibility (Smith, 2012), allowing for the emergence of unforeseen yet locally significant findings.

### 2.4.2 Ecological data

Ecological data was analysed using SPSS (IBM) v.23.0 (2015) statistical software. For the Analysis of Variance (ANOVA), normality assumptions were verified using the Shapiro-Wilk test (Shapiro & Wilk, 1965). This test was preferred over alternative normality tests (such as Kolmogorov-Smirnov) due to its utility for sample sizes below 50 and its greater statistical power for detecting departures from normality (Razali & Wah, 2011; Mendes & Pala, 2003). Levene's test (Levene, 1960) was used to verify the homogeneity of variances assumption. Seeing as ANOVA is robust to violation of normality when heterogeneity of variances is met (Quinn & Keough, 2007) its use was also justified when these conditions arose.

Each quadrat was assigned a dieback value according to Wylie's dieback index (WDI) (Wylie, 1986; modified for three health classes) which is derived by weighted linear combination (see McGarigal *et al.* 2013):

$$WDI = \%\text{healthy trees x } 0.01 + \%\text{sick trees x } 0.03 + \%\text{dead trees x } 0.05$$

This resulted in a dieback score (WDI) ranging from one to five (Table 3). Mean WDI was compared between alive and dead quadrat types using one-way ANOVA.

**Table 3 -** Dieback severity according to Wylie's Dieback Index (Wylie, 1986).

| Dieback index | Dieback severity |
|---|---|
| **1.00** | no dieback |
| **1.01 - 2.00** | slight to moderate |
| **2.01 - 3.00** | moderate to severe |
| **3.01 - 4.00** | severe |
| **4.01 - 4.99** | very severe |
| **5.00** | dead |

A chi-square test of independence (Pearson, 1900) was performed to examine the relationship between height class and health class. Bonferroni post hoc tests were performed in order to elucidate which height classes were significantly related to which health classes. The significance level (α) was corrected for the number of comparisons according to the Bonferroni procedure (Bonferroni, 1936). In doing so, the health classes (healthy, sick or dead) that dominated each height class was determined. These analyses facilitated interpretations of tree size and health structure based on ecological theory. Hence vulnerable and resilient height classes were identified with a focus on "alive" quadrats as this gave insight into recent trends in stand demography (Ens *et al.* 2010).

Multiple linear regression (MLR) was used to investigate the correlation between the measured independent variables (IVs) and WDI. Normality of errors was verified using the Shapiro-Wilk test. Presence of outliers in all variables was verified by requiring all Cook's distances (Cook, 1977) to be less than one (Cook & Weisberg, 1982) and requiring that the range of standardised residuals lay between -3 and 3. Multi-collinearity between IVs was verified by requiring Pearson's correlation coefficient (Pearson, 1896) to be less than 0.7. A linear relationship between the IVs and Wylie's dieback index was verified through visual inspection of residuals plots.

Five different MLR models utilising different combinations of explanatory variables were produced based on the strength of Pearson's correlation coefficient between the IVs and WDI. $R^2$ and $R^2$ adjusted ($R^2_{adj}$) were reported for each MLR model, however the latter was preferred as it is suited to small sample sizes (Mittlböck & Schemper, 2002) and takes into account the number of parameters in the model (Quinn & Keough, 2007). Statistical significance of each model was based on the significance of the change in the F statistic i.e. the difference between the fitted linear regression model and the comparison model: mean Y = X. Variables that significantly contributed to the linear fit of each MLR model were identified by the standardised β for each IV and the associated p value.

# 3 Results

## 3.1 Traditional Owner knowledge about *Melaleuca* spp. dieback

Nvivo thematic analysis of interviews with six TOs identified 16 responses that converged on seven suspected causes of *Melaleuca* dieback (Figure 8). The majority of responses (45.5%) implicated saltwater. Buffalo and pigs were implicated as frequently as each other (27.3% each). Cyclones were the third most frequently suggested cause (18.2%). The least frequent explanatory factors were climate change, mangroves and uncertainty (a single response each). Of course the latter may not be a cause *per se*, but was relevant to include for a holistic analysis of TO viewpoints on *Melaleuca* dieback. It also may suggest that the semi-structured interviews did not force responses; instead it may have allowed them to emerge appropriately.

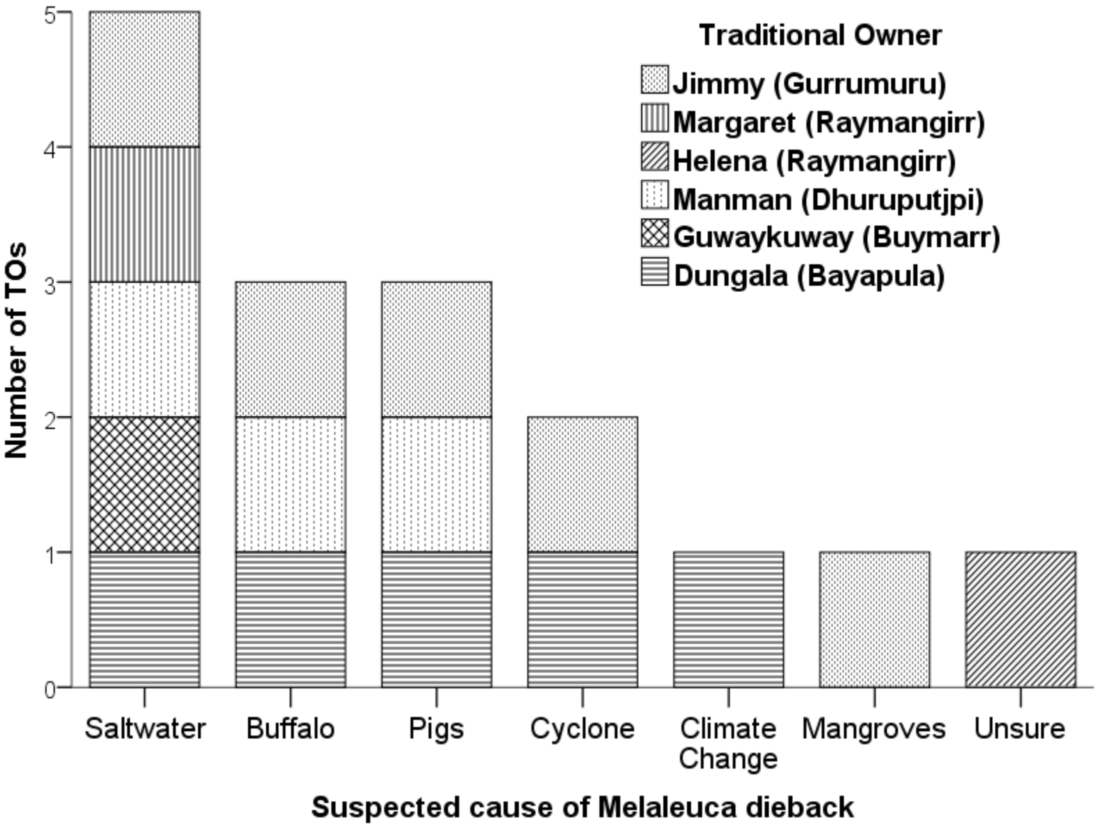


**Figure 8 -** Traditional Owners' (TOs) viewpoints on the causes of *Melaleuca* spp. dieback on their Homeland. TOs first names are given with the Homeland they spoke for in brackets.

Seeing as thematic analysis provided a useful, yet simplified, visualisation of TOs' viewpoints on *Melaleuca* dieback, the following sections of this thesis will explore key points highlighted during semi-structured interviews that contextualise and personalise the knowledge shared by each senior TO. These conversations were analysed qualitatively, on a study site basis, for the purpose of ensuring that scientific investigations of the ecological landscape were attuned to the cultural dimensions embodied by these landscapes.

*Gurrumuru*

**Figure 9 -** Jimmy Wunungmurra, Gurrumuru Traditional Owner.

Senior Gurrumuru TO, Jimmy Wunungmurra had been thinking about *Melaleuca* spp. dieback (primarily *M. cajuputi*) on his Homeland for some time (Figure 9). In addition, he had noticed the coincident disappearance of water chestnut (*Eleocharis* spp.), a highly sought after bushfood known locally as rạ̈kay. Jimmy was one of the main TOs who had expressed concern to researchers regarding the dieback and as a result had become a key co-researcher on the project.

*"Before, that area was strong and healthy and there was rạ̈kay before. Rạ̈kay was everywhere before. This is the story of Gurrumuru. I was worrying and the people are hurting because the land is being damaged. How will we help bring the land back to life?"*

Jimmy had considered a range of possibilities regarding the causes of dieback. He also implicated feral ungulates in the death of older trees:

*"The old ones* [*Melaleuca* spp.] *are dying. I think the feral animals like pigs and buffalo* [are responsible]. *The buffalo and pigs are digging the roots, then that kills the trees."*

It was clear from Jimmy that he thought a range of factors were combining to the detriment of the trees.

*"Pigs and buffalo make channels along the coastline area, then the rain comes down through the channels and meets with saltwater, then the saltwater comes to billabong area and damages the trees. When the rain comes down it makes buffalo channels bigger, sometimes it brings mangroves… Then the rain came down with the cyclone and brought mangrove seeds and small plants to the paperbark area. Then mangroves grow near the riverbank and kill the paperbark trees… now this water is saltwater. Two waters mixing galimidirrk widiyarr* [new water] *came from the river bank."*

Jimmy's explanation suggested that the channels being made by the feral animals were assisting the saltwater intrusion towards the *Melaleuca* trees, especially during times when the river is high. It was noteworthy that he believes the saltwater is coming from the surface, rather than from underground. Jimmy went on to suggest that in addition to the channel effects produced by feral ungulates, there were also more direct impacts as well:

*"When the feral animals came they started damaging trees and digging the roots."*

While the dieback was distressing to the people of Gurrumuru, it appeared that some were making the most of the situation through cultural use of the dead *Melaleuca* spp.:

*"The old people use the dead trees as wood for fire making. Every middle of the dry season the old people come and burn the dead trees."*

Regarding solutions to the dieback problem, Jimmy presented his views that the culling of pigs and buffalo by the Yirralka Rangers had positive results for the land:

*"The rąkay is back again because the Rangers were shooting the feral animals. Here at Gurrumuru and the other homelands too."*

It appeared that the rąkay (*Eleocharis* spp.) were coming back, but Jimmy did not say anything about the *Melaleuca* spp. Jimmy's view was that there is still more work to be done to address the issue:

*"We are now doing water monitoring and mud monitoring to find out why the trees are dying… That's why we bring these boys* [Yirralka Rangers] *to do the monitoring work here at Gurrumuru. We have to put the mark on the inland area* [quadrat marking posts]."

### *Raymangirr*

**Figure 10 -** Margaret Wanambi, Raymangirr Traditional Owner.

**Figure 11 -** Helena Wanambi, Raymangirr Traditional Owner.

Raymangirr TOs, Margaret and Helena Wanambi (Figures 10 & 11) noted that the health of *Melaleuca viridiflora* on their Country had declined over the years; as Margaret explained:

*"Before all the trees were alive and healthy. From the trunk to the branches and the leaves plus the roots it was all alive, healthy and strong. The root was standing strong because of the freshwater underground."*

Margaret explained that the underground freshwater that kept *M. viridiflora* alive also carried cultural significance:

*"The old people came near to the trees and dug underground to the ground water. The people came and dug the hole near the roots of the paperbark tree when they were thirsty…And the freshwater was used for drinking and having a bath. There are two water holes, one here and one there used for drinking and having a bath."*

Helena expanded on this cultural significance through telling the story of the wallaby that took the water a long time ago:

*"The wallaby came with the basket* [water container] *and grabbed the water and left to hide somewhere. That Country's name is Gurandaka. This time Yolŋu don't know why the paperbark trees are dying."*

From the historical knowledge contained within the story, one interpretation is that there was a time in the past when the freshwater had disappeared; possibly leading the *Melaleuca* spp. of the time to die off. This contrasted with the present dieback, as Helena believed that Yolŋu are unsure why the trees are dying. However, Margaret offered an explanation as to why she thought *M. viridiflora* were dying. Again the dieback of rąkay (*Eleocharis* spp.) was observed as coincident with the dieback of trees:

*"Saltwater and freshwater met each other underground. When the salt and freshwater meet together they kill the roots of the paperbark trees. Before rä̧kay was strong and healthy because of the freshwater."*

Margaret attributed the *M. viridiflora* dieback to saltwater. It was also notable that the impacts of feral animals were not mentioned by either of the Raymangirr TOs.

### *Dhuruputjpi*

**Figure 12 -** Manman Wirrpanda, Dhuruputjpi Traditional Owner.

Manman Wirrpanda, Dhuruputjpi TO (Figure 12), told the researchers that multiple *Melaleuca* species were dying on his country and that the dieback was relatively recent:

*"We getting problem with the dharpa* [trees], *with the nambarra tree* [*M. cajuputi*] *and also with the dhulgu* [*M. leucadendra*] *standing around* [dying] *there because we did not have this before."*

Manman linked the dieback with saltwater intrusion, before going further to say that the latter phenomena was also recent:

*"At the start of the homelands movement…we didn't have this sort of kind of fresh and saltwater coming together."*

According to Manman saltwater intrusion and the associated *Melaleuca* dieback had happened around the time that the pigs and buffalo arrived and started making channels. Both at Dhuruputjpi and other floodplain areas:

*"The pigs and the buffaloes came 'round; we don't know where they came from. They just… walk along the track going to the floodplain. And when they do go 'round they try and make some sort of road* [channel] *going through from the salt* [water] *to the fresh* [water] *from the fresh to the salt. And we didn't know about this until we got the surprise of this water damaging our trees. Along the floodplain and also in other* [flood] *plain countries. But this things hasn't been before but it's now happening."*

Regarding whether the saltwater is coming from the surface or underground, Manman was unsure:

*"Because of the* [salt] *water we don't know* [if] *it's going underground, underneath and coming up towards meeting this freshwater."*

Regardless of where the saltwater was coming from, Manman considered the impacts to be a significant eco-cultural issue:

*"That is why the salt and the fresh can't live together. Because of damaging those plants. Coming up. That's the place when you saw it and I know it's very, it's a shameful job for like you know for us Yolŋu people to live in both* [fresh and saltwater]. *You know saltwater and freshwater combining."*

Manman held out hope that a solution could be reached, as long as Yolŋu and western scientists keep working together:

*"But are there somehow we can try to help each other to do plan come up balance same again. Yolŋu and ŋapaki* [non-Aboriginal people] *balancing together. Doing the djama* [work]."

## *Buymarr*

**Figure 13 -** Guwaykuway Wanambi spoke for his uncle's Country at Buymarr.

Guwaykuway Wanambi (Figure 13) spoke to the researchers about his uncle's Country: Buymarr. Lirrpya Mununggurr from the Yirralka Rangers (Figure 14) also contributed his views about the area. Guwaykuway believed that the main cause of the *Melaleuca acacioides* dieback was saltwater:

*"Saltwater is killing the trees. Saltwater and freshwater mix together."*

Guwaykuway also suggested that the saltwater was coming from under the ground, rather than from surface flows:

*"The saltwater came underneath and killed the paperbark trees."*

Lirrpya Mununggurr from the Yirralka Rangers suggested that although the *M. acacioides* were dying, the area was still considered relatively healthy for other reasons:

"*This billabong is called Gunumbul… This Country is good, there's lots of geese coming to the billabong. A lot of animals come to that billabong like buffalo* [and] *pigs*."

**Figure 14 -** Lirrpya Mununggurr, Yirralka Ranger.

Buffalo and pigs visiting the area was not suggested to be detrimental to the eco-cultural health of the site; neither Guwaykuway nor Lirrpya suggested that these feral ungulates were contributing to *M. acacioides* dieback at Buymarr. Rather, the land's attractiveness to buffalo and pigs suggested that this was "good" Country. However, the loss of rą̣kay (*Eleocharis* spp.) had been observed by Lirrpya and other Yolŋu with saltwater being the suspected cause:

*"I think there is no more rą̣kay left because of the saltwater. Before, that billabong had a lot of rą̣kay. Now there's none left."*

*Bayapula*

Dungala Mununggurr, the djungaya (legal officer under Yolŋu Law) of Garthalala (homeland near Bayapula floodplain), spoke with the researchers about Bayapula (Figure 15). Dungala wasn't sure how long ago the *Melaleuca* spp. started dying:

*"[The trees started dying] some time. Month. Some time. Long time."*

**Figure 15 -** Dungala Mununggurr, djungaya for Garthalala (homeland near Bayapula floodplain).

Dungala believed that the main cause of the *M. acacioides* dieback was saltwater, both from surface and sub-surface flows, primarily due to high tides and cyclones.

*"Saltwater. Coming with the tide. High tide coming in… sometimes the water comes from underneath; the salty water. When the high tide or cyclone [comes], the water was coming in into to where that paperbark tree* [is found]."

While Dungala did not link the activities of feral animals explicitly to dieback, he did convey a sense of some of their impacts on *M. acacioides*, suggesting that they could be involved. In particular he mentioned how buffalo use the trees as scratching posts and that there had been a noticeable increase in the local pig population:

*"The buffaloes there, they put their body [on the tree] and scratch you know"… Wild pigs. They are breeding more."*

Dungala concluded the semi-structured interview by suggesting that climate change may have caused or been related to the observed saltwater intrusion:

*"The climate difference you know changing. Yeah, change around. The weather change."*

## 3.2 Comparison of "dead" and "alive" *Melaleuca* spp. areas at different sites

Visual inspection of the five study sites shows that there were distinct areas of "alive" and "dead" trees (Figure 17). There was also variation in the *Melaleuca* species present at each study site (Table 4), although all three *Melaleuca* species encountered were exhibiting stand-level dieback. Density (*Melaleuca* stems/ha) varied by quadrat type and species (Figure 18; Table 4). There was no consistent trend as "alive" quadrats at Dhuruputjpi and Bayapula had higher densities than "dead" quadrats, whereas the opposite was true at Gurrumuru, Raymangirr and Buymarr. As such differences in density between quadrat types were insignificant ($F_{1,8}$ = 1.061, p = 0.333; Figure 18). Bayapula "alive" had by far the highest stem density due to high juvenile recruitment and suckering of *Melaleuca acacioides*. Species richness (of living plants) tended to be higher in "alive" *Melaleuca* quadrats than "dead" *Melaleuca* quadrats. However, the difference was statistically insignificant ($F_{1,8}$ = 2.959, p = 0.124).

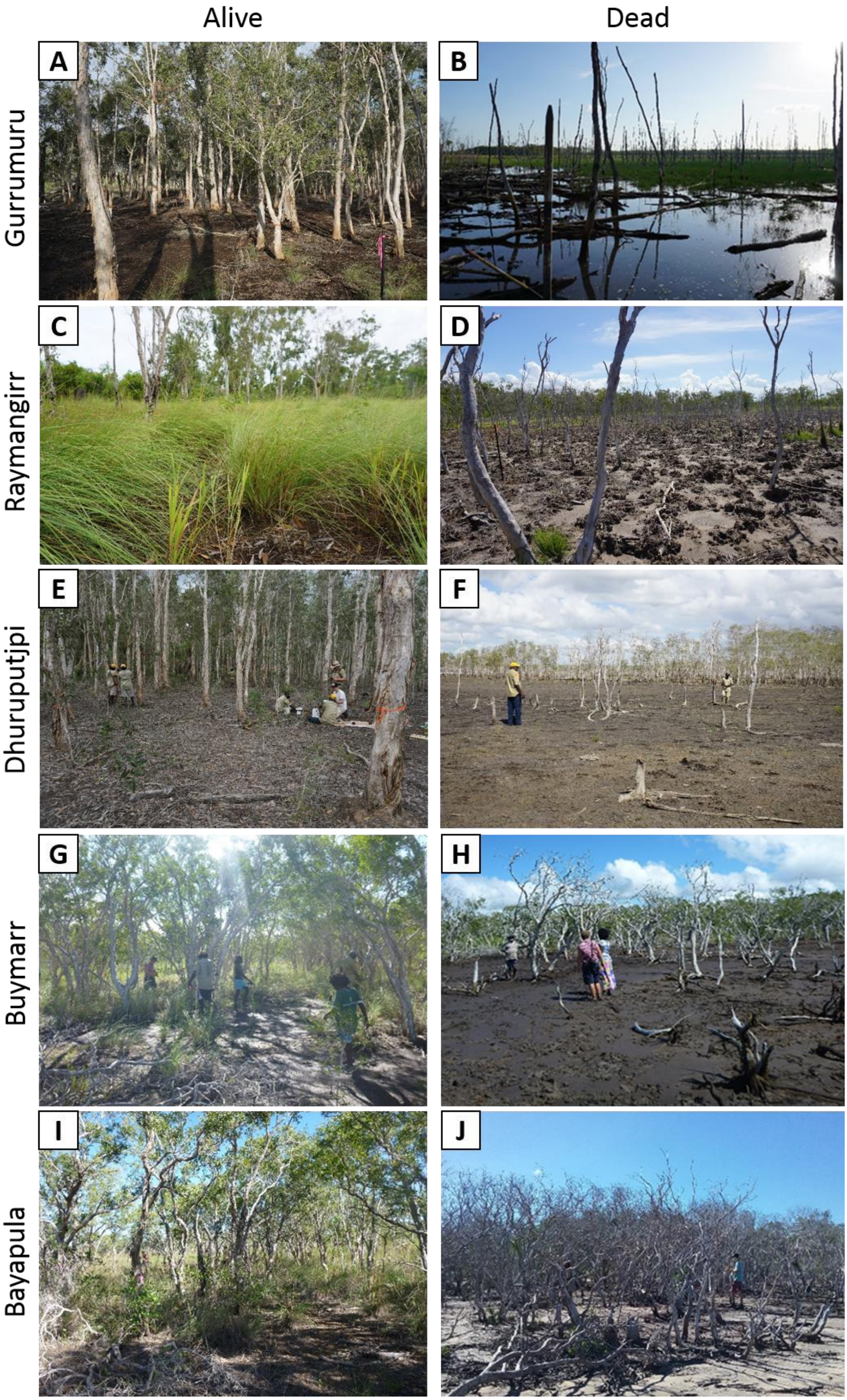


**Figure 17 –** Representative images of each “alive” (left column) and “dead” (right column) quadrat that was ecologically sampled at each study site (rows).

**Table 4 -** *Melaleuca* species present at study sites.

| Study site | *Melaleuca* species present | Quadrat type | Density (stems/ha) | Species richness | Wylie's dieback index |
|---|---|---|---|---|---|
| **Gurrumuru** | *M. cajuputi* | Alive | 500 | 2 | 1.2 |
| | | Dead | 750 | 1 | 4.93 |
| **Raymangirr** | *M. viridiflora* | Alive | 900 | 5 | 1 |
| | | Dead | 1450 | 3 | 4.86 |
| **Dhuruputjpi** | *M. cajuputi* & *M. viridiflora* | Alive | 2800 | 9 | 1.46 |
| | | Dead | 625 | 4 | 5 |
| **Buymarr** | *M. acacioides* | Alive | 1100 | 7 | 1.14 |
| | | Dead | 1300 | 0 | 4.65 |
| **Bayapula** | *M. acacioides* | Alive | 6975 | 11 | 2.79 |
| | | Dead | 1875 | 8 | 4.76 |

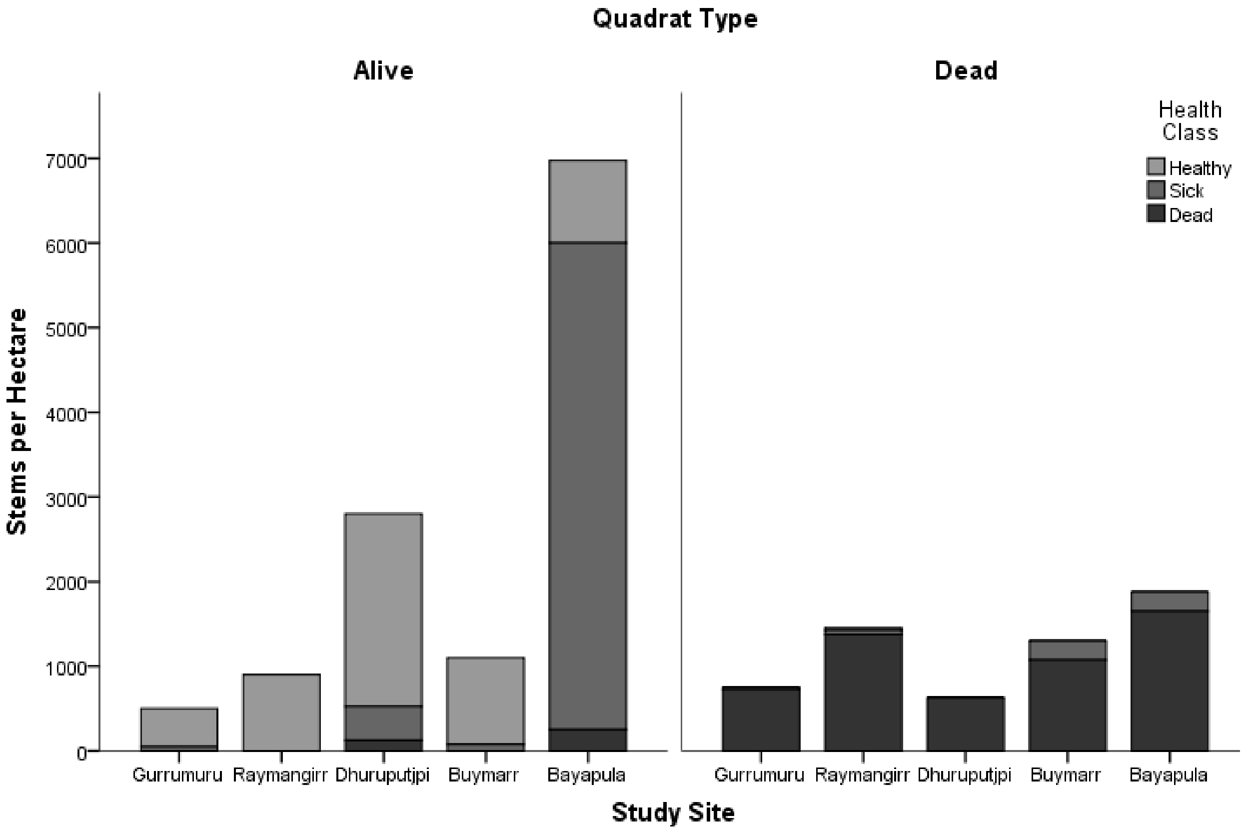


**Figure 18 -** Density (stems/ha) of Melaleuca in "alive and "dead" quadrats at each study site. Bars are stacked according to health class.

Comparison of Wylie's dieback index between quadrat types was highly significant ($F_{1,8}$= 99.625, $p < 0.001$), which validated that quadrat selection generally represented clearly definable "alive" and "dead" areas. One possible exception was Bayapula "alive" which had a WDI representing moderate to severe dieback (Wylie, 1986) or an intermediate ("sick") state (Figure 19).

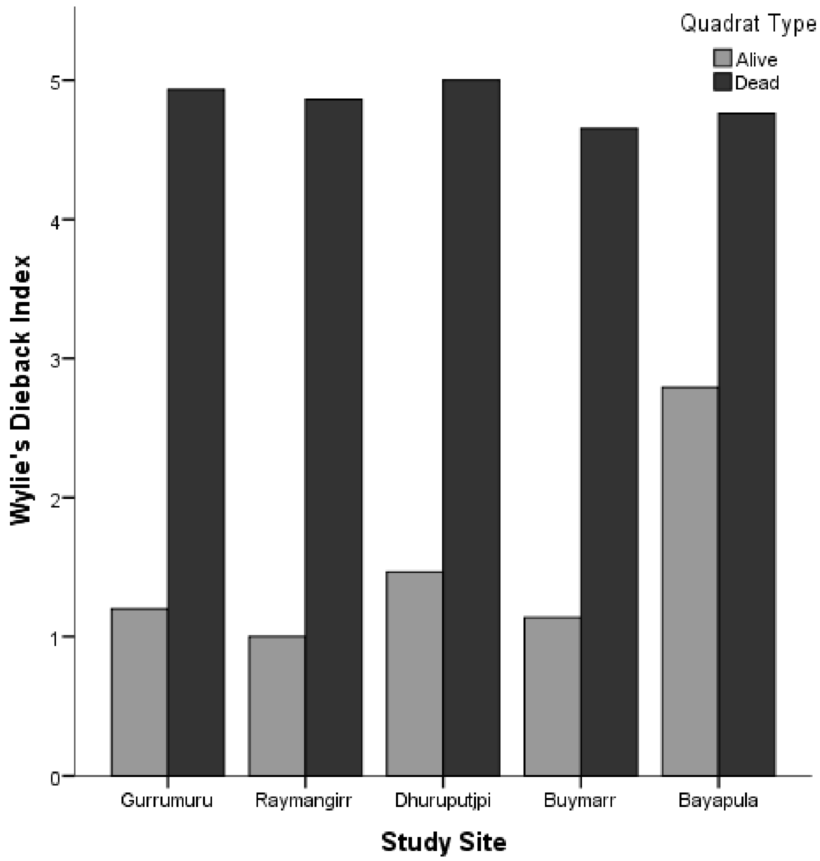


**Figure 19 -** Wylie's dieback index (WDI) for each quadrat type and study site.

## 3.3 *Melaleuca* demography and stand health within study sites

In "alive" quadrats, in the <1m and 1-2m height classes, there were similar mean proportions of sick stems and healthy stems. In the 2-5m height class, the mean proportion of healthy stems was approximately triple the mean proportion of sick stems. In the 5-10m height class, there were far greater proportions of healthy stems than sick stems. In the >10m height class, there was a greater mean proportion of healthy stems than sick stems. Thus "alive" quadrats appeared to show a sick-healthy continuum that followed an ordinal gradation from shorter to taller height classes. In contrast, "dead" quadrats displayed far greater mean proportions of dead stems than healthy or sick stems in all height classes except for the >10m class where no stems occurred.

A chi-square test of independence was performed to examine the relationship between height class and health class. It was revealed that health class was significantly related to height class in "alive" quadrats (Chi-square = 83.669, df = 8, $p < 0.001$) but not in "dead" quadrats (Chi-square = 4.014, df = 6, $p = 0.675$). Bonferroni post hoc tests were performed on "alive" quadrats in order to elucidate which height classes were significantly related to which health classes. The significance level α was corrected for the number of comparisons (15) according to the Bonferroni procedure (Bonferroni, 1936); i.e. $\alpha = 0.05/15 = 0.003$. It was revealed that the 5-10m height class had the strongest statistically significant relationship to health class. In this height class, 89.2% of stems were healthy, which was significantly higher than expected under the null hypothesis of no relationship ($p < 0.001$). Additionally, in this height class, 9.2% of stems were sick which was significantly lower than expected ($p < 0.001$). As such, "alive" quadrat stems 5-10m tall were significantly more likely to be healthy and significantly less likely to be sick than other height classes. These findings demonstrate that in "alive" quadrats the 5-10m height class was the most resilient to declines in health. Seeing as 65.3% of stems in the <1m height class were sick, it was expected that sickness would be highly related to this height class. However, the relationship was not statistically significant ($p = 0.042$).

## 3.4 Investigating potential and actual acid sulfate soils

Mapping of data from the Australian soil resource information system (ASRIS) revealed the possibility of acid sulfate risk at all study sites and elsewhere in the Laynhapuy IPA (Figure 20). Whilst Gurrumuru is clearly located in a high probability zone, Dhuruputjpi is marginal as it lies on the cusp of high and low probability areas. The expected status of Raymangirr, Buymarr and Bayapula are less clear as they are located in regions of no data (Figure 20).

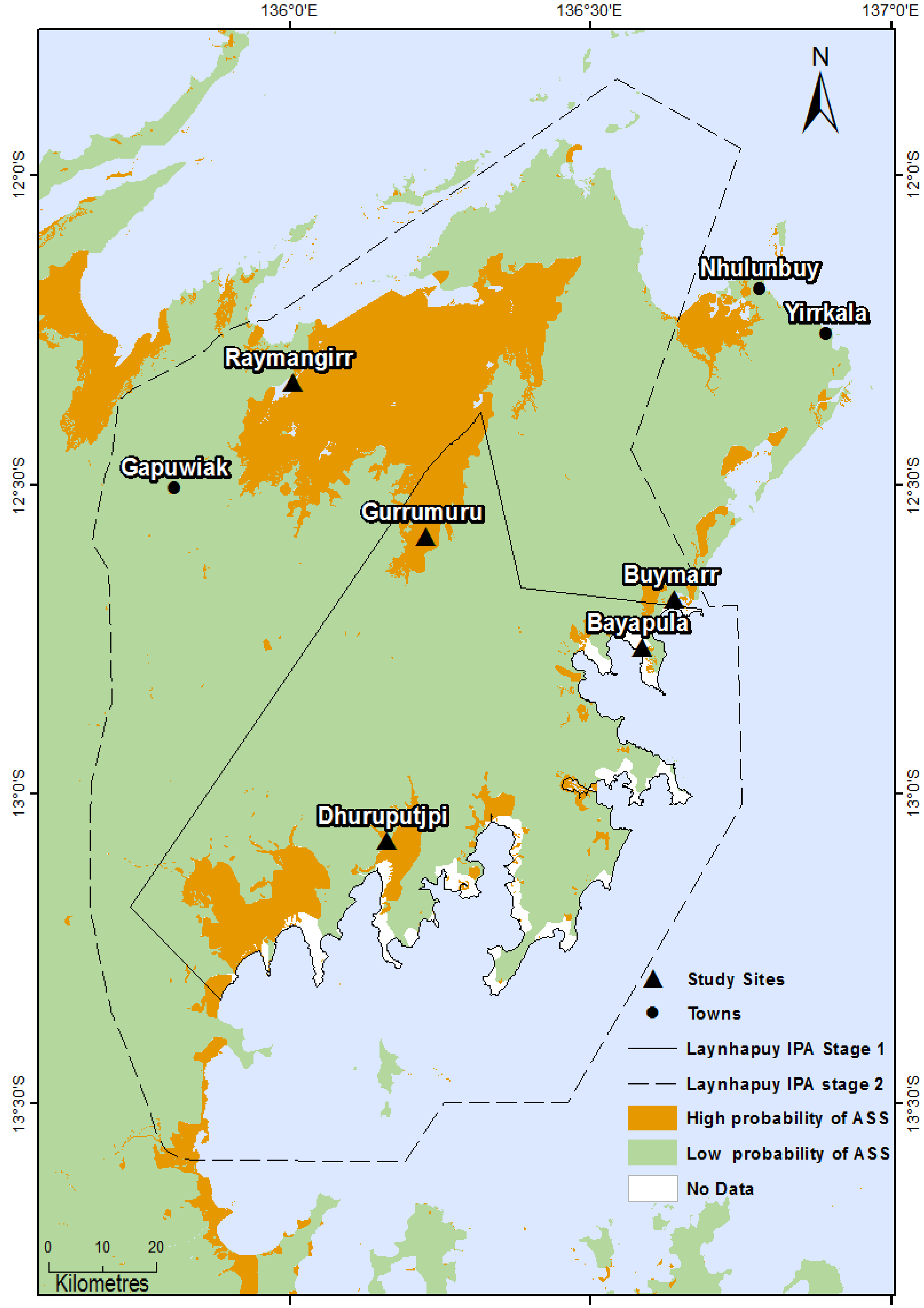


**Figure 20 -** Acid sulfate soil (ASS) risk in NE Arnhem Land. Map generated by the author in ArcMap v.10.3.1 (ESRI) using data from the Australian soil resource information system (ASRIS, 2016). Probability is based on theoretical knowledge regarding terrain types where acid sulfate soils typically occur; usually water-logged environments with a coastal influence.

In order to ground truth theoretical expectations of acid sulfate soil (ASS) presence (Figure 20) and determine whether acid sulfate soils were implicated in *Melaleuca* dieback, soil samples were tested for pH at 10 cm and 50 cm depths in the soil profile. Actual ASS was indicated when the minimum pH at 0 minutes was below 4. Potential ASS was indicated when the minimum pH was below 4 after 3 minutes of oxygen exposure. Results are detailed in Table 5.

**Table 5 –** Mean, minimum and maximum pH of soil at 10 cm and 50 cm depths at all quadrats and study sites. Actual and potential acid sulfate soils are indicated in red.

| Study site | Quadrat type | Mean 10 cm soil depth pH at 0 mins (min-max) | Mean 10 cm soil depth pH at 3 mins (min-max) | Mean 50 cm soil depth pH at 0 mins (min-max) | Mean 50 cm soil depth pH at 3 mins (min-max) |
|---|---|---|---|---|---|
| **Gurrumuru** | "alive" | 4.53<br>4.00 - 5.58) | 3.63<br>(3.54 - 3.71) | 3.83<br>(3.65 - 4.01) | 3.54<br>(3.45 - 3.64) |
| | "dead" | 4.69<br>(4.40 - 4.9) | 4.55<br>(4.12 - 5.11) | 4.64<br>(4.49 - 4.90) | 4.35<br>(4.21 - 4.48) |
| **Raymangirr** | "alive" | 6.44<br>(6.01 – 7.00) | 5.90<br>(5.68 - 6.14) | 5.97<br>(5.64 - 6.50) | 5.75<br>(5.65 - 5.94) |
| | "dead" | 7.33<br>(5.58 – 10.00) | 5.45<br>(5.41 - 5.47) | 5.65<br>(5.44 - 5.90) | 5.04<br>(4.50 - 5.45) |
| **Dhuruputjpi** | "alive" | 7.00<br>(7 - 70) | 6.32<br>(6.22 - 6.41) | 6.38<br>(6.2 - 6.56) | 6.76<br>(6.4 - 7.11) |
| | "dead" | 7.70<br>(5.70 - 11.10) | 5.83<br>(5.49 - 6.150) | 6.67<br>(6.60 - 6.70) | 6.52<br>(6.36 - 6.73) |
| **Buymarr** | "alive" | 6.00<br>(5.00 – 7.00) | 4.15<br>(3.97 - 4.33) | 4.90<br>(4.90 - 4.90) | 3.86<br>(3.75 - 3.96) |
| | "dead" | 5.70<br>(4.70 - 6.70) | 4.29<br>(4.11 - 4.47) | 5.00<br>(5.00 – 5.00) | 3.91<br>(3.80 - 4.01) |
| **Bayapula** | "alive" (sick) | 5.67<br>(5.30 - 5.92) | 5.42<br>(4.87 - 5.76) | 5.20<br>(4.96 - 5.50) | 4.53<br>(4.30 - 4.65) |
| | "dead" | 5.12<br>(4.35 - 6.60) | 4.88<br>(4.24 - 5.87) | 4.80<br>(4.09 - 5.60) | 4.48<br>(4.04 - 5.08) |

Actual ASS was indicated at Gurrumuru Alive (50 cm depth). Potential ASS was indicated at Buymarr "alive" and "dead" (50 cm depth). All other quadrats were above the threshold value of pH four (Table 5) indicating an absence of ASS.

Across study sites and quadrats, the 50 cm depth generally had a lower starting and finishing pH than the 10 cm depth. The exceptions were both Dhuruputjpi quadrats where starting pH for the 10 cm depth was higher than the 50 cm depth, but after 3 minutes these ranks were reversed (Figure 21). The most precipitous drops in pH typically occurred within 30 seconds to one minute after soil was exposed to air (Figure 21). This indicated that oxidation of sulfide into sulfuric acid was extremely rapid.

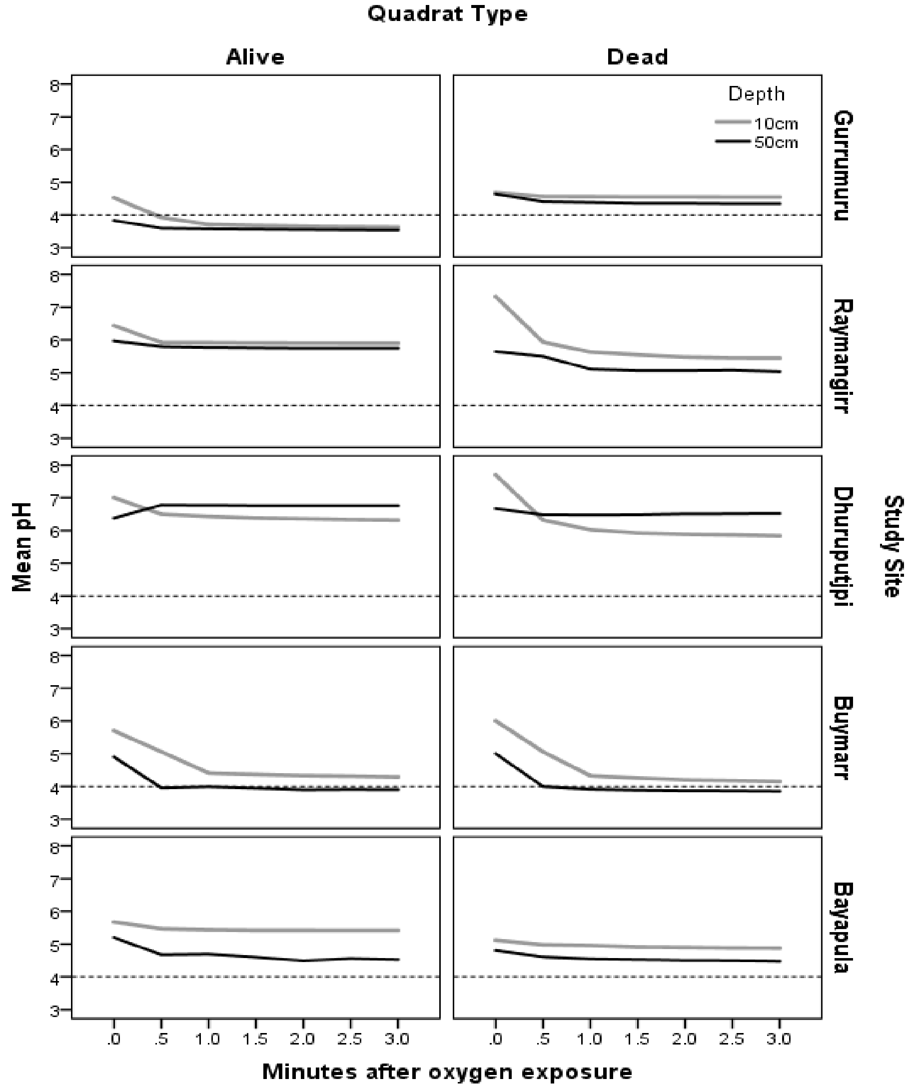


**Figure 21 -** Soil pH change every 30 seconds (0.5 minutes) after oxygen exposure. The dashed reference line at pH 4 indicates where acid sulfate soils are likely to be present.

## 3.5 Which factors predict *Melaleuca* spp. dieback?

Multiple linear regression (MLR) models were utilised to determine which factors predicted *Melaleuca* dieback (Table 6). All MLR models met the assumptions, except MLR3 which violated Cook's distance. MLR2 had the highest $R^2_{adj}$ value, and the greatest model significance ($p = 0.014$), suggesting that the proportion of feral damage (i.e. combined buffalo and pig damage) and soil EC at 10 cm depth best predicted Wylie's dieback index (Table 6; MLR2). Analysis of standardised β's revealed that for every one standard deviation (SD) increase in proportion feral animal damage (i.e. 0.256), Wylie's dieback index increased by 0.682 SD (i.e. 1.24) on average. For every one SD increase in 10 cm EC (i.e. 6.937 mS/cm), Wylie's dieback index increased by 0.606 SD (i.e. 1.1) on average. Together feral animal damage and 10 cm EC accounted for 70.1% of the variation in Wylie's dieback index. MLR3 demonstrated that pig and buffalo impacts are highly similar. Standardised β's were identical to three decimal places (std $\beta = 0.565$, $p = 0.04$). In addition MLR3 had a higher $R^2$ than MLR2, although model significance was less (Table 6).

Regarding significant predictors, pH at 10 cm soil depth at time 0 (pH T0) and proportion ground cover were not flagged as significant in any of the models. Conversely, proportion feral animal damage and EC at 10 cm soil depth (10 cm EC) were flagged as significant in the majority of MLR models. Proportion feral animal damage was considered to be more significant than 10 cm EC in all models where both of these parameters were significant. However, when proportion feral animal damage was separated into proportion pig and proportion buffalo damage (as in MLR3), 10 cm EC was more significant than the former two.

**Table 6 -** Five different multiple linear regression models using Wylie's dieback index as the dependent variable.

| Model | Independent variables | $R^2$ | $R^2_{adj}$ | F (df) | p value |
|---|---|---|---|---|---|
| **MLR1** | 10 cm pH T0, prop. ground cover, species richness, 10 cm EC, prop. feral damage | 0.725 | 0.380 | 2.104 (5,4) | 0.245 |
| **MLR2** | 10 cm EC, prop. feral damage | 0.707 | 0.624 | 8.458 (2,7) | 0.011 |
| **MLR3** | Prop. pig damage, prop. buffalo damage, 10 cm EC | 0.859 | 0.606 | 5.611 (3,6) | 0.036 |
| **MLR4** | Prop. feral damage, 10 cm EC, prop. ground cover | 0.708 | 0.563 | 4.858 (3,6) | 0.048 |
| **MLR5** | Prop. feral damage, 10 cm EC, 10 cm pH T0 | 0.720 | 0.581 | 5.154 (3,6) | 0.042 |

Considering that feral animal damage and 10 cm EC were the most significant predictors of dieback, a deeper exploration of these factors was warranted. Mean proportion buffalo damage was greater in “dead” quadrats than “alive” quadrats (Figure 22b), although not statistically significant ($F_{1,8}$ = 1.203, p = 0.305). However, Raymangirr and Buymarr exhibited buffalo damage in “alive” quadrats only. Proportion buffalo damage was highest at Dhuruputjpi regardless of quadrat type, followed by Gurrumuru (Figure 22a). Mean proportion pig damage was greater at “alive” quadrats than “dead” quadrats (Figure 22d) although not statistically significant ($F_{1,8}$ = 1.554, p = 0.248). However, pig damage was highly variable across study sites, with Raymangirr “dead” showing the highest proportion of damage whilst Dhuruputjpi and Buymarr displayed no pig damage (Figure 22c). Amalgamation of buffalo and pig damage yielded proportion feral animal damage. Mean proportion feral animal damage was significantly higher in “dead” quadrats than “alive” quadrats (Figure 22f) although not statistically significant ($F_{1,8}$ = 4.241, p = 0.073). Feral damage was higher in “dead” quadrats than “alive” quadrats at all study sites except for Buymarr (Figure 22e).

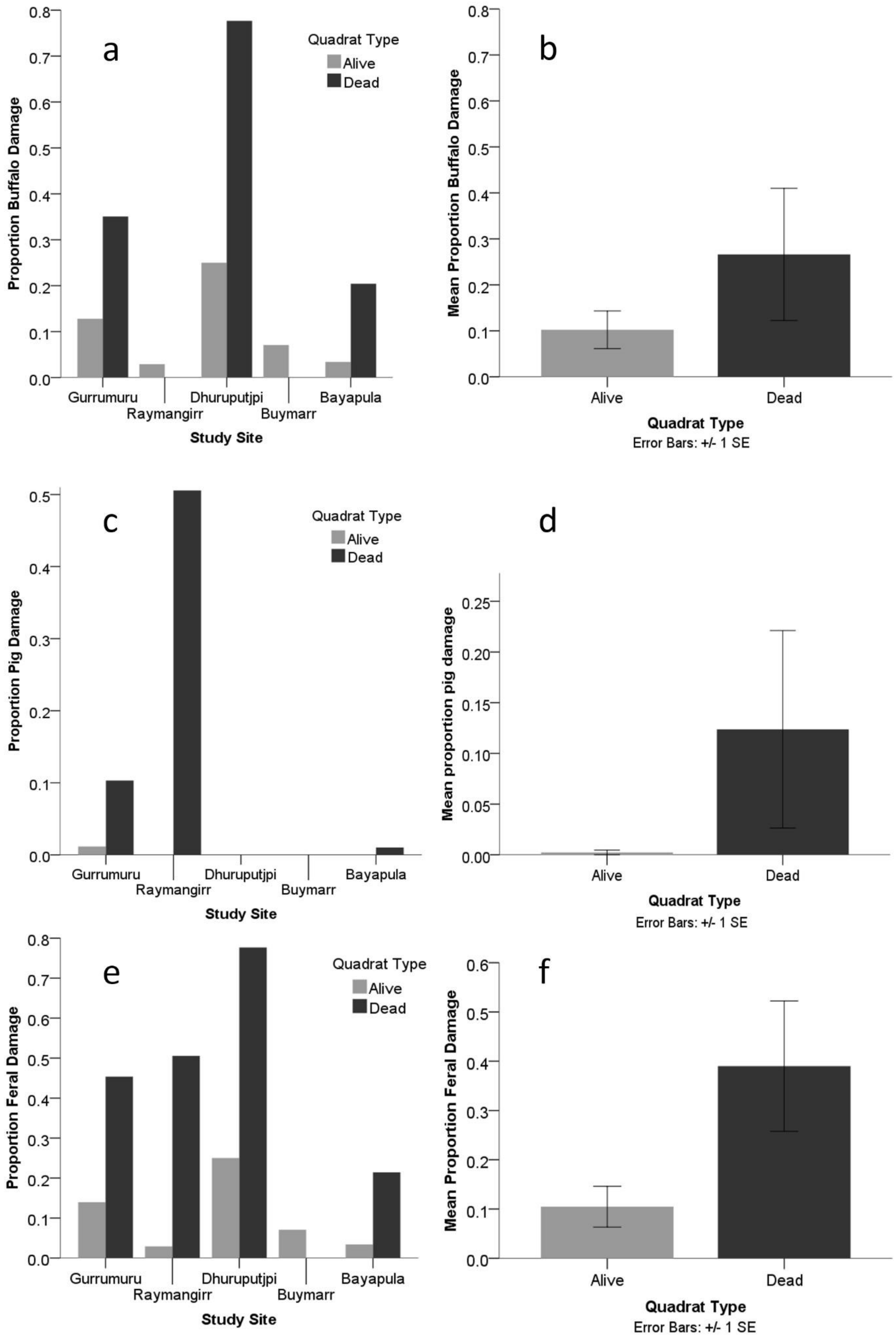


**Figure 22 –** (a) Proportion buffalo damage at each study site, clustered by quadrat type. (b) Mean proportion buffalo damage at "alive" and "dead" quadrats ±1SE. (c) Proportion pig damage at each study site, clustered by quadrat type. (e) Mean proportion pig damage at "alive" and "dead" quadrats ±1SE. (f) Proportion feral animal damage at each study site, clustered by quadrat type. (g) Mean proportion feral animal damage at "alive" and "dead" quadrats ±1SE.

There was high variability in mean soil EC between study sites as well as quadrat type. “dead” quadrats exhibited a significantly higher mean soil EC than “alive” quadrats at the 10 cm depth ($F_{1,22}$ = 4.677, p = 0.042). At 50 cm soil depth, “dead” quadrats tended to display a higher mean soil EC than “alive” quadrats (Figure 23), although the difference was insignificant ($F_{1,22}$ = 1.863, p = 0.1863). Dhuruputjpi was anomalous in this case as it was the only site which displayed a higher mean EC in the “alive” quadrat than the “dead” quadrat at 50 cm soil depth.

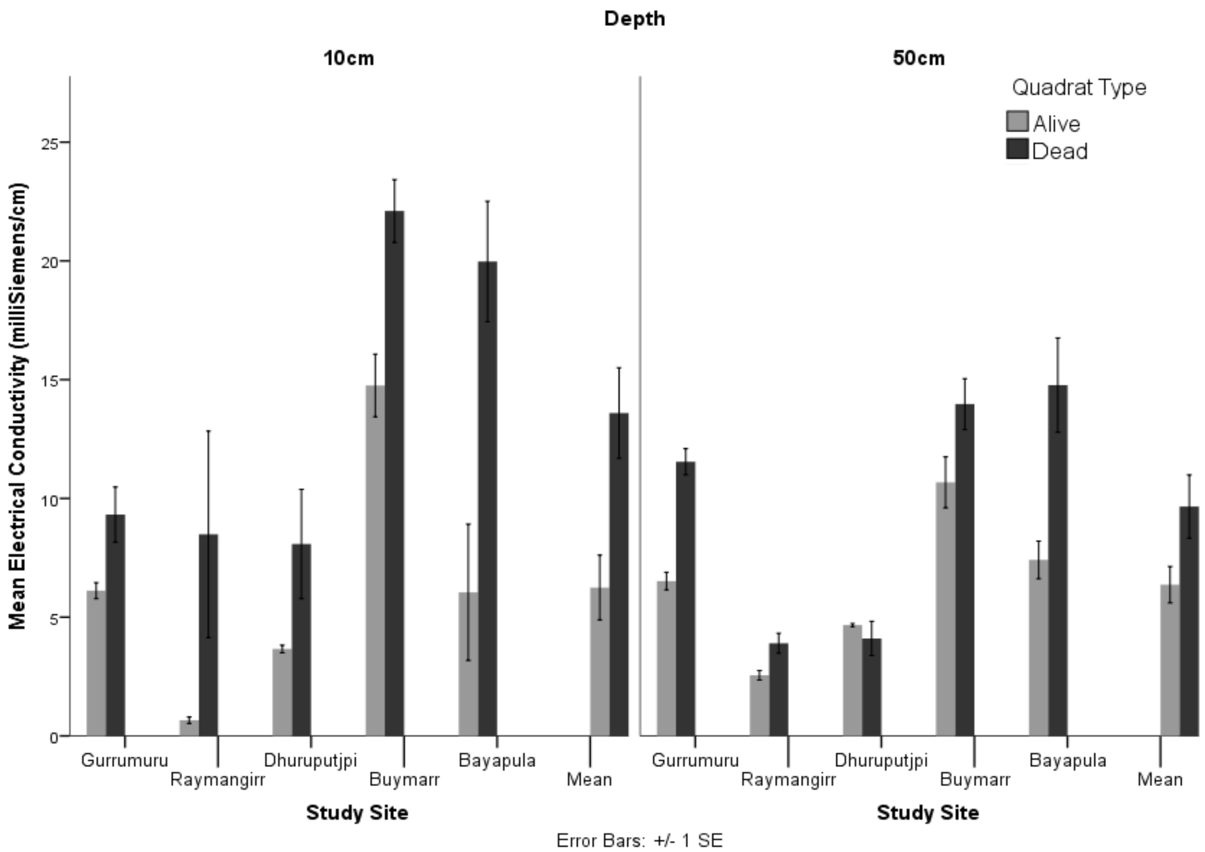


**Figure 23 -** Electrical conductivity (EC) at each study site (10 cm and 50 cm depth), clustered by quadrat type.

# 4 Discussion

Using eco-cultural mixed methods analysis, this study found that the key drivers of *Melaleuca* spp. dieback. in the Laynhapuy IPA, north-east Arnhem Land are likely to be feral animals and salinity. This study has provided on ground evidence for the likely causes of dieback in collaboration with Traditional Owners, which up until now has been lacking in the scientific literature. Parallels between socio-cultural and ecological data were elucidated by the significant agreement between TO identified causes of *Melaleuca* dieback and multiple regression models (MLRs). It is remarkable that 68.8% of TO responses (11/16) included saltwater and feral animals whilst MLR2 (10 cm soil depth EC and proportion feral animal damage) explained 70.7% of the variance in dieback. Furthermore, each approach made suggestions about other likely contributing factors that the other approach did not: TOs suggested cyclone impacts and ecological analyses suggested acid sulfate soils. It is well known that senior Traditional Owners often have a high level of knowledge regarding changes on their land (Muller, 2014; McGregor *et al.*, 2010; Robinson *et al.*, 2005; Whitehead *et al.* 2003) and the value of including Indigenous collaborators in ecological research is supported by the present study. In addition to building a research design centered on local concerns and mutual benefit (Smith, 2012), the remarkable complementarity between local Indigenous knowledge and Western science suggests that an eco-cultural approach to research on Aboriginal owned land can provide additional outcomes that outweigh use of only one approach.

## 4.1 Likely causes of *Melaleuca* dieback in northern Australia

Congruous with generalised tree dieback theories (Ross & Brack, 2015; Landsberg & Wylie, 1988; Mueller-Dombois, 1988; Wylie, 1986), both local knowledge holders and the scientific research found that multiple factors are likely to be responsible for *Melaleuca* spp. dieback. The range of TO responses indicated (i) multiple causes of dieback converging on two primary causes, namely salinity and feral ungulates and (ii) a combination of general causes with the potential for some study site idiosyncrasies. As detailed in the results section, Gurrumuru TO, Jimmy described the combined impacts of ecological factors on *Melaleuca* spp. dieback:

*"Pigs and buffalo make channels along the coastline area, then the rain comes down through the channels and meets with saltwater, then the saltwater comes to billabong area and damages the trees"*

This local knowledge is aligned with observations by Fogarty (1982) who reached similar conclusions regarding the interaction of feral ungulates, saltwater intrusion and *Melaleuca* dieback in the Kakadu region. Eco-cultural data from this study and the broader scientific literature provided the means to interpret the likely causes of *Melaleuca* dieback in the context of chain reaction theory (Mueller-Dombois, 1988). As conveyed in the thesis introduction, chain reactions resulting in dieback can be conceptualised as following predisposing, precipitating (pressures) and trigger factors (pulses) (Mac Nally *et al.* 2014; Mueller-Dombois, 1988). In relation to *Melaleuca* dieback in the Laynhapuy IPA, these factors are more thoroughly examined below.

## 4.2 Predisposing factors: Canopy monospecificity, ecotone dynamism and micro-elevation

In the present study predisposing factors included stand structure, floodplain fringe ecotone dynamism, and possibly extreme edaphic conditions. With regard to stand structure, all study sites (except Dhuruputjpi) exhibited monospecificity, typical of *Melaleuca* forest (Department of the Environment and Water Resources, 2007). Due to the synchronicity of life cycles (Harper, 1982; Sarukhan & Harper, 1973) and the similarity of ecological tolerances (Archibald, 1995), monospecific cohorts often experience higher rates of mortality than those with greater species richness (Mueller-Dombois, 1988; Harper, 1982; Sarukhan & Harper, 1973). Seeing as all quadrats except Raymangirr "alive" displayed a lack of juvenile recruitment (Appendix 3), there is reason to expect that the life cycles of the remaining plants may be in close synchrony or on the verge of synchrony; although phenological studies would be required to confirm this. If this is the case, the "alive" quadrats studied (with the exception of Raymangirr) may be at risk of dieback. These quadrats need ongoing monitoring to determine if this occurs in the future.

The second predisposing factor is the extreme edaphic conditions found on the fringes of coastal floodplains. The dynamic ecotone that occurs at the interface of the semi-saline and freshwater vegetation communities, to which *Melaleuca* species typically belong (Cowie *et al.* 2000), are subject to seasonally variable temperature, moisture and salinity; the tolerances for which are reflected in the particular *Melaleuca* species present (Cowie *et al.*, 2000; Table 2). These ecological pressures are exemplified by wet season high tides. For example, consistent with the ecological tolerance reported by Levitt (1981), *M. acacioides* was found at Bayapula; a floodplain which, like the other study sites, is subject to wet season high tides. Garthalala (Bayapula) djungaya, Dungala, believed that the high tides were exerting deleterious effects on *M. acacioides* (gulun 'kulun*)*. Therefore, edaphic conditions oscillate between saturated to dry and semi-saline to fresh, during monsoonal wet and dry seasons, at this and other floodplains to varying degrees. Paradoxically, stand-level dieback events may occur in species with wide ecological tolerances, as the species is able colonise varied habitats and begin to dieback at the ecotones once conditions change beyond threshold limits (Archibald, 1995). This study suggests that such a phenomena may have occurred at the coastal floodplain study sites. In accordance with Cowie *et al.* (2000), the observed variability in EC (surrogate for salinity) between study sites reflected the live *Melaleuca* species present at each site. As such, *M. viridiflora* was found at the lowest salinity sites (Raymangirr and Dhuruputjpi), *M. cajuputi* was found at the medium salinity sites (Dhuruputjpi and Gurrumuru), and *M. acacioides* was found at the highest salinity sites (Bayapula and Buymarr). It was unexpected that *M. acacioides* was found at higher salinity sites than *M. cajuputi,* as Van der Moezel *et al.* (1991) found the reverse salinity tolerances in juvenile plants of these species. Although, these differences in observed salinity tolerances may be due to intraspecific variations (Niknam & McComb, 2000; Van der Moezel *et al.* 1991), life stage, or the snapshot nature of this study. Interestingly, *M. viridiflora* and *M. cajuputi* were both found at Dhuruputjpi; in which "alive" quadrat soil EC levels were above those measured at Raymangirr and below those measured at Gurrumuru where these species were found respectively. This suggests that these two species have different, yet overlapping tolerances to salinity. Although different *Melaleuca* species have different inundation and salinity tolerances (Cowie *et al.* 2000; Van der Moezel *et al.* 1991), all species may be affected by salt once it exceeds their specific threshold level and if other dieback related factors are present.

Differences in micro- and macro-elevation (Bowman *et al.* 2010; Applegate, 1999; Mulrennan & Woodroffe, 1998) and distance from the ocean (Mulrennan & Woodroffe, 1998) have previously been implicated in *Melaleuca* spp. dieback elsewhere. Applegate (1999) has also reported that as little as 10 cm elevation difference is enough to inhibit a range of freshwater grasses. Differences in micro-elevation, (classed as vertical changes up to approximately 30 cm: Husson *et al.* 2000), were apparent at all sites, but this was especially obvious at Gurrumuru. The "dead" quadrat was obviously at a slightly lower elevation (approximately 10 cm) than the "alive" quadrat, as can be seen by the difference in inundation (cf. Figure 17A and 17B). Further detailed studies of the micro-elevational changes throughout floodplains could significantly inform predictions regarding the interaction of sea level rise, saltwater intrusion, feral ungulate impacts and *Melaleuca* dieback. Approaches accurate enough to capture micro-relief could include light detection and ranging (LiDAR; laser altimetry) (Jensen, 2016), stereo-photogrammetry (3D imaging drone technology) (Sužiedelytė-Visockienė, 2013) and/or differential GPS (Jensen, 2016).

Acid sulfate soils (ASS) have been implicated in *Melaleuca* dieback elsewhere (Webb *et al.* 2016) and desktop research suggested that ASS may have been implicated at some sites in the present study. However, negligible pH change (using the ASS test) was found close to the surface; not enough to be classed as potential ASS for three of five study sites given that the final pH values were greater than four. Notable exceptions were Gurrumuru and Buymarr which displayed mean pH values below four after three minutes in both the "alive" and "dead" quadrats; characteristic of potential ASS (Department of Environment Regulation, 2015; Stone *et al.* 1998; Hartikainen & Yli-Halla, 1985). These results align with existing published ASS modelling in the area and represent some of the first ground truthing that is known to the author. However, it cannot be ignored that MLRs did not show any sign of a relationship between pH and dieback, suggesting that soil pH at 10 cm and 50 cm depths may not be significant general causes of *Melaleuca* dieback. However, this does not rule out the possibility that ASS may be occurring at some study sites and therefore be contributing to localised dieback. Also, considering that the 50 cm soil depth corresponds to the root zone of juvenile *Melaleuca* (McClean *et al.* 2011), the lack of relationship may be due to inadequate depth measurements. As such, future studies may need to examine depths below 50 cm to determine the pH of soil at the root zone of adult *Melaleuca* spp. Just as *Melaleuca* species were similar across the "alive" and "dead" quadrats at each site, yet monospecific canopies are likely to be a predisposing factor for dieback, soil pH may follow suit in its ability to predispose *Melaleuca* to dieback without showing any significant difference between "alive" and "dead" quadrats. As such, it is not expected that predisposing factors must be significantly different between "alive" and "dead" stands to have an impact. As such, the impact of pH cannot be ruled out. Further research could elucidate these findings as they are only snapshots of soil pH at particular times, places and depths.

## 4.3 Precipitating factors: Buffalo, pigs and salinity

As expected from the literature, precipitating factors identified in this study were attributed to the pressures of increased salinity and feral ungulate (buffalo and pig) impacts. These were the most common causes of *Melaleuca* dieback stated by TOs (Figure 8), were greater in "dead" quadrats that "alive" quadrats on average (Figures 22 & 23), and were the most significant predictors of dieback in the MLRs (Table 6). It is also a major finding from this study that combined impacts of feral animals were more significant than salinity. As Jimmy and Manman explained, the creation of channels by feral ungulates is likely to be aiding the intrusion of saltwater towards the floodplain margin where *Melaleuca* forest occurs, resulting in dieback. The landscape scale impacts of these can be seen in Figures 24 and 25. The synergistic effects of feral ungulates and saltwater intrusion are in line with previous remote sensing studies in the Kakadu region (Bowman *et al.* 2010; Mulrennan & Woodroffe, 1998; Fogarty, 1982; Stocker, 1970). Additionally, this study builds on work by Ens *et al.* (accepted) who also concluded that feral buffalo and salinity (in addition to ammonium and turbidity) were related to *Melaleuca* dieback in freshwater billabongs (without a coastal saline influence) of northern central Arnhem Land (near Maningrida). Considering that the former study found increased salinity at billabongs, due to buffalo activity and excrement, it is conceivable that buffalo may be contributing to increased soil salinity in the present case through these means in addition to the channel effects. Further research is required to disentangle direct and indirect floodplain salinisation due to buffalo and potentially pigs as well.

**Figure 24 -** Buffalo swim channels (Cowie *et al.*, 2000). Photo: F. Woerle.

**Figure 25 -** Buffalo swim channel at Dhuruputpi. Photo: D. R. Sloane**.**

In addition to increasing salinity, feral animals are likely to have other negative impacts on *Melaleuca* spp. and other vegetation. Jimmy suggested that pigs were not only creating channels, but also digging around the roots of *Melaleuca* spp., potentially allowing for even greater saltwater intrusion and perhaps exposure to other factors such as microbes. Other TOs did not mention this, so this effect may be especially prevalent at Gurrumuru, or it could be that other TOs are not as connected and aware about detailed changes to their Homelands like Jimmy is. However, if the former is correct, this may explain why surface EC (10 cm depth) was greater than subsurface EC (50 cm depth) in "dead" quadrats at all study sites except Gurrumuru where EC was similar at both depths. In general, greater EC at the surface than the subsurface suggests that tidal flooding may be responsible (Stocker, 1970), but it may be possible that the Gurrumuru situation is related to pig digging increasing the depth of saltwater infiltration. However, if this was the case, a more pronounced EC at 50 cm soil depth should have been observed at Raymangirr where pig damage was five times higher.

As other studies have found, feral ungulates have other deleterious impacts on vegetation (McKnight, 1971) such as trampling (Ens *et al.* 2016; Bird, 2008; Petty *et al.* 2007; Williams, 1984) and grazing (Bird, 2008; Werner *et al.* 2006) which may contribute precipitating pressures on *Melaleuca* stands by hindering regeneration of young plants (Cabin *et al.* 2000). This may explain the poor sapling regeneration at Gurrumuru and Buymarr but does not explain the sapling regeneration at Raymangirr, Dhuruputjpi and Bayapula. Simultaneously, salt levels may have become prohibitively high for older trees, resulting in dieback. Ferals digging and exposing roots of old trees (Williams, 1984) may have also contributed to the dieback, and TOs communicated this during interviews. However, it was surprising that the Dhuruputjpi "alive" quadrat had the highest proportion of feral damage and the highest proportion of juvenile (<1m) regeneration.

Studies in Kakadu National Park, by Werner *et al.* (2006) found that buffalo presence initially increased growth of juvenile trees (<1.4m, mostly Eucalypts and pantropical species), compared with buffalo absence. However, this was followed by increased dormancy. The effects of feral ungulates on vegetation are complex and may differ depending on environment (e.g. floodplain vs. savanna) and species. In order to disentangle the effects of feral ungulates on *Melaleuca* dieback as well as juvenile and canopy recruitment at coastal floodplains, there is a need for ongoing longitudinal study of these factors. This could allow for the creation of dieback and recruitment models similar to Crowley *et al.* (2009) who measured and modelled the effects of storm burning on *M. viridiflora* demography at Cape York Peninsula. Such a model could provide valuable insight for Yirralka Rangers' management practices at Laynhapuy IPA, and for other north Australian coastal ranger groups.

While much of the literature on *Melaleuca* spp. dieback in northern Australia has focused on buffalo impacts, this study has shown that pig impacts may be equally significant for *Melaleuca* spp. dieback. Jimmy suggested that pigs caused more damage than buffalo. Although mean proportion of pig damage was not as high as mean buffalo damage, MLR3 (pig damage, buffalo damage, 10 cm EC) showed that the effect of pig and buffalo damage on dieback were almost identical; as can be seen from the identical standardised coefficients (Table 6). While $R^2$ of MLR2 (Feral animal damage and 10 cm EC) and MLR3 (buffalo, pig damage and 10 cm EC) were very high (0.707 and 0.859 respectively), it is possible that these could be improved with more quadrat and site replication.

It is also important to note that the snapshot nature of the study may have influenced the results as the lag time between buffalo occupation and impacts can be significant (Bowman *et al.*, 2010; Petty *et al.*, 2007). TOs explained some of the reasons for these lag effects. They suggested that rates of feral ungulate channel erosion were related to rainfall, high tides, and cyclones. Over time these processes result in feral ungulate channel dimensions increasing to the point when they can transport saltwater in ample quantities to kill *Melaleuca* spp. Mulrennan & Woodroffe (1998) have reached similar conclusions to the TOs in this study when they suggested that tidal creek evolution, and therefore saltwater intrusion, could not have been caused by buffalo alone at the Tommycut and Sampan Creeks at the southern end of the Van Diemen Gulf (east of Darwin). They also implicated wet season storm surge, rainfall variability and especially, powerful cyclone events in the initiation and exacerbation of rapid tidal creek extension. These suggestions echo similar findings by Williams (1984) (see also Cowie *et al.* 2000; Werner *et al.* 2006) who additionally implicated late dry season fires as a potential contributing factor to *Melaleuca* dieback. Early wet season fire (storm burning) has been demonstrated to reduce recruitment of *M. viridiflora* to the sapling class and in the sustained absence of such fires, increased recruitment to the canopy has been predicted (Crowley *et al.* 2009). While the TOs that participated in the present study made no mention of fire, and the *Melaleuca* trees exhibited no visible fire scars, the present study did not systematically examine fire as a potential contributor to dieback. As such, further research on this is required.

While ecological surveys found no evidence of pig damage and little evidence of buffalo damage at Buymarr, Yirralka Ranger, Lirrpya mentioned that pigs and buffalo frequent the area; highlighting the limitations of the snap-shot ecological data. Therefore, in order to build a more complete understanding of the dynamic interactions of feral animal and saltwater impacts on the health of *Melaleuca* spp. and other culturally significant species such as rạ̈kay (*Eleocharis* spp.), there is a need for ongoing monitoring to address these knowledge gaps. In addition to their likely impacts on *Melaleuca*, pigs are known to eat rạ̈kay (*Eleocharis* spp). TOs mentioned rạ̈kay repeatedly, probably due in large part to its cultural value as bushfood. Rạ̈kay and *Melaleuca* dieback were often mentioned in tandem, suggesting that the dieback of these species may have coincided with each other. Considering that rạ̈kay is a known food source for pigs (Corbett, 1995), this may partly explain why levels of pig and buffalo damage were highly variable between study sites; perhaps reflective of the particular food sources available for each. For example, Gurrumuru had no rạ̈kay in the "alive" area and lots of rạ̈kay in "dead" area. Jimmy believed that the rạ̈kay had come back because the Yirralka Rangers had been shooting the feral ungulates, suggesting that the effect of these animals on rạ̈kay was significant.

Numerous previous studies in the Kakadu region have implicated salinity in *Melaleuca* dieback (Cobb *et al.* 2007; Winn *et al.* 2006; Bell *et al.* 2001; Applegate, 1999; Cobb, 1997; Knighton *et al.* 1992; Woodroffe *et al.* 1986; Williams, 1984; O'Neil, 1983; Fogarty, 1982; Stocker, 1970). This study also found salinity was strongly related to *Melaleuca* dieback. Mean EC and NaCl measured at floodplains during this study (excluding sites dominated by *M.acacioides*) was similar to other studies that measured this (see Cobb, 1997; Stocker, 1970). This suggests that similar levels of salinisation appear to be related to dieback of *M. viridiflora, M.cajuputi* and possibly *M. leucadendra.* Glasshouse trials show some different results for seedlings as *M. leucadendra* has demonstrated 93.3% survival after 24 months of 7.93mS/cm (Sun & Dickinson, 1995). In another glasshouse trial, *M.cajuputi* was shown to have a higher salinity tolerance than *M.acacioides* (Van der Moezel *et al*. 1991). This is at odds with the present field observations in which *M. acacioides* was found living in higher salinity environments (Buymarr and Bayapula) than *M. cajuputi* (Gurrumuru, Dhuruputjpi). This is not surprising as *M. acacioides* is known to grow on the landward side of mangroves (Brophy *et al.* 2013; Wrigley

& Fagg, 1993) in areas subject to saltwater flooding (Levitt, 1981). Accordingly, mangroves were observed at Bayapula approximately 200m away from *M. acacioides* dieback. *M. viridiflora* has the lowest salt tolerance of the *Melaleuca* spp. observed (Van der Moezel *et al.* 1991) and consequently, it was found at the sites with lowest salinity (Raymangirr & Dhuruputjpi). Due to rising sea levels (White *et al.* 2014; Steffan *et al.* 2009), with 17- 38cm predicted global mean rise by 2046-2065 (IPCC, 2013), feral ungulate occupation (Saalfield, 2014) and the accelerating rate of saltwater intrusion in the Northern Territory since the 1980's (Steffan *et al.* 2009), salinity may continue to increase at all sites well into the late 21st century. This may result in further *Melaleuca* dieback.

## 4.4 Trigger factors: Cyclones

While the ecological aspects of study were designed to include a number possible correlates of *Melaleuca* dieback, it is clear that the list of measured factors was not exhaustive. In particular, TOs repeatedly raised the issue of cyclones contributing to saltwater intrusion in pulse events. This is viewed as a particularly important area for future research as cyclones were not mentioned by the researcher during semi-structured interviews. This meant that reflexivity (Breuer *et al.* 2002) or "leading the witness" between researchers and TOs was ruled out on this issue. Cyclones have been suggested to cause dieback of *Melaleuca* directly through wind throw (Webb *et al.* 2016; Williams, 1984) and indirectly through tidal creek extension (Winn *et al.* 2006; Mulrennan & Woodroffe, 1998). Cyclones have also been reported to leave lasting deleterious impacts on trees that survive the event, probably due to xylem damage leading to lasting adverse effects on water transport (Ueda & Shibata, 2004). While cyclone impacts were not obvious during primary data collection in 2016, they may have been observed during the 2015 preliminary study phase at Buymarr in 2015; as seen by snags leaning over at this site (Figure 2A). Increased cyclone activity associated with climate change is also predicted to occur in the late 21st century, though early 21st century predictions are less certain (IPCC, 2013). As TOs and the published literature both converge on the effects of cyclones on dieback, combined with the possibility that this may increase into the future, there is a need to further investigate the effects of cyclones on *Melaleuca* dieback. This may provide an explanation of some of the MLR variance unaccounted for by feral ungulates and salinity, thus providing a vital key towards a more complete understanding of present and future causes of *Melaleuca* dieback.

## 4.5 Measuring dieback

Wylie's dieback index (WDI) proved a useful metric for assessing stand health. This was demonstrated through the identification of Bayapula alive as an outlier due to a low proportion of healthy stems, as the majority proportion of stems were sick rather than healthy or dead. There is one issue with the index however: only trees that are present are included within it. If a floodplain has had its trees swept away by cyclones, floods or another mechanism, these trees will not contribute to the dieback index. Snags getting swept away by wind (Webb *et al.* 2016; Mueller-Dombois, 1991), would also explain the general lack of trees over five metres tall in dead quadrats. Time series aerial photography and use of normalised vegetation index (NDVI) may provide a solution to this problem when it is available; however it was not available for this study at the resolutions required to discern changes under 30 m in forest extent. Another solution could be to include a density dependent parameter into the dieback index that assists analysis of changes in forest health over time. This would require knowledge of expected healthy densities of particular *Melaleuca* species in order to gauge deviations from this. In this study however, stems/ha were not significantly different between "alive" and "dead" quadrats suggesting that other solutions require exploration.

## 4.6 The benefits and challenges of a two-way eco-cultural approach to research

From the initial research concept, through to the identification of study sites and potential causal factors, and the collection of ecological data, TOs were central to the process. This study found that *Melaleuca* spp. dieback is prevalent across at least three different species (*M. viridiflora*, *M. cajuputi, M. acacioides*) (Tables 4 & 7, Figures 17 & 19) and possibly dhulgu (*M. leucadendra*) as identified by the Dhuruputjpi TO, Manman. While the latter species was not confirmed by ecological surveys, the salinity measured at Dhuruputjpi (Figure 23 & Appendix 3) combined with species' preference for slightly brackish water (Ahmad, 1997; Sun & Dickinson, 1995), suggests a reasonable possibility that *M. leucadendra* may exhibit stand-level dieback where it occurs at other sites. Further field verification is required to confirm this hypothesis.

While the mutual benefits of cross-cultural research were manifold, many challenges were faced during this research from which several key lessons can be distilled. Firstly, once common goals have been agreed on, there must be a recognition that Indigenous and non-Indigenous researchers have vastly different educational backgrounds and resulting priorities and modes of engagement with different types of research. From the point of view of Western scientists, an emphasis on rigorous and time consuming data collection is central to doing robust science. It is imperative that all research participants understand how to collect data and the importance of careful data collection in order for the results to be presented with confidence. As a result, data collected in this study by a range of people needed to be vetted.

As this study has shown, TOs already had a significant understanding of the causes of *Melaleuca* spp. dieback on their land. The perceived folly of going to such extraordinary effort to find out what TOs already know may present a challenge to undertaking robust science in cross-cultural settings. Science is a long and arduous process; would it not be more efficacious to ask TOs what they have observed on their Country? But this also relies on strong connection and plenty of time being spent on Country, which in some cases does not happen as much as others. Yolŋu TOs in this study and elsewhere, have acknowledged that science is valuable to IPA management, provided that TOs are the key integrators of Indigenous and scientific knowledge (Davies *et al.* 2013). This study demonstrated some such benefits from doing the science: through the allocation of numbers to the various causal factors, the proportional contribution of each factor was able to be estimated quantitatively.

In doing so the groundwork has been laid for the creation of models that may be able to predict future changes in the distribution of *Melaleuca* spp. in northern Australia. More immediately, the quantification provided in this study may allow for the maximisation of an effective management response through the proportional allocation of management resources dedicated to addressing the likely causal factors of *Melaleuca* dieback.

Given the knowledge that Yolŋu people often have spiritual beliefs about unusual occurrences on Country (e.g. Ens, 2012), there is more work to be done to understand the spiritual connections that Yolŋu have to *Melaleuca* species in this area. Jimmy spoke about people getting sick because the land was sick, providing insight into eco-cultural implications for Indigenous health and livelihoods, and further, the intertwined co-becoming of people and Country (Bawaka Country *et al.* 2015). The suggestion that the health of Country is related to the health of people echoes the findings of the healthy Country, healthy people project (Garnett & Sithole, 2007), lending further support to the value of combined ecological and cultural methods to research on Aboriginal land and in collaboration with Aboriginal people. When Raymangirr TO, Helena, spoke about the wallaby who took water away from beneath the ground in the past, this suggested that there is more historical knowledge and spiritual insight to be gleaned from continued collaborative research. It will take time to develop the trust necessary for such meaningful exchanges between Yolŋu and Western scientists. This clearly represents a sustained endeavour (Davies *et al.* 2008; Wolfe, 1993) that must always be grounded in a strong ethos of reciprocity, respect and mutual benefit (Smith, 2012).

Another challenge faced regarding the synthesis of Yolŋu and Western scientific knowledge was related to matching Yolŋu matha names for *Melaleuca* species (especially nambarra and raŋan) with the scientific names of these species. This has strong implications for collaborative two-way research as it is imperative that a common understanding of taxonomic nomenclature be held in order to maximise effective synergy of these two ontologies. Through speaking with TOs and Rangers during the course of this study it had become clear that there is some discord between the Yolŋu names local people used and those given in local authoritative texts such as Yunupiŋu *et al.* (1995) and Charles Darwin University's Yolŋu matha dictionary (Zorc *et al.* 2014). While examining alignment between taxonomic systems was not a focus of the present study, it is reasonable to propose that addressing these possible inconsistencies may pave the way for improved future collaborations between Yolŋu people, Western scientists and environmental managers.

## 4.7 Implications for environmental management

While there is potential to improve the confidence of the study findings through increased sample sizes and longer term monitoring, there are several management relevant findings that can be distilled. This study has found that pigs, buffalo and salinity are likely to be the key drivers of *Melaleuca* dieback (with potential for cyclones, acid sulfate soils and micro-elevation to be included). As such management efforts and action research aimed at mitigating *Melaleuca* dieback should focus on addressing these likely causes.

Firstly, in terms of feral animal impacts, a key finding from a management standpoint is that in general pigs and buffalo may be equally harmful to *Melaleuca* species; with their combined impacts being slightly more significant for dieback than salinity alone. There is also some potential for floodplain idiosyncrasies, as Jimmy has stated that pigs are worse than buffalo whilst other TOs did not mention the impacts of ferals at all. These findings are in line with others who have found that despite the damaging effects of feral animals on the landscape in Aboriginal owned northern Australia, perceptions regarding the impact and management of ferals differ considerably (Ens *et al.* 2016; Albrecht *et al.* 2009; Robinson *et al.* 2005). It is uncertain whether the differential effects of feral animals were related to local abundance or other factors.

Regarding the mitigation of further *Melaleuca* dieback, the finding that pig and buffalo impacts may be highly similar (Table 6) suggests that equal resources could be devoted to culling pigs and buffalo. Culling is already a major part of the Yirralka Rangers management strategy (Wettenhall *et al.* 2014), though there is potential to modulate this as needed and as new information becomes available. Jimmy believed that rä̱kay was coming back to Gurrumuru because the rangers had been shooting ferals, suggesting positive results. As such, the effects of culling on the regeneration of rä̱kay and *Melaleuca* spp. will need to be monitored closely in order to quantify the input-return ratio.

Other solutions to feral animal impacts have utilised exclusion fences (Ens *et al.* 2016; Werner *et al.* 2006; Cabin *et al.* 2000). Overall, this technique can be quite effective at promoting native plant regeneration (Ens *et al.* 2016; Cabin *et al.* 2000), but it would be impractical to erect fences around vast floodplain areas (Tengia *et al.* 2016). A more feasible approach may include consulting with TOs about high priority areas for protection, such as sacred sites, and fencing around these.

As there is likely to be a lag time between feral ungulate occupation and saltwater intrusion in northern Australia (Bowman *et al.* 2010; Petty *et al.* 2007) there is a need to better understand the relationship between feral abundance and ecological change over time. This knowledge would improve the ability to produce predictive maps of saltwater intrusion and *Melaleuca* dieback. Accurate modelling and prediction of future impacts may hold particular management importance for Yirralka Rangers and other ranger groups in northern Australia, as this knowledge could integrate with TO knowledge to inform identification of priority sites for protection such as culturally and ecologically significant areas that may become vulnerable to saltwater intrusion in the near future.

Attempts have been made to reduce saltwater intrusion and enhance *Melaleuca* regeneration through the construction of barrages (Winn *et al.* 2006; Winn, 2001; Applegate, 1999; Mulrennan & Woodroffe, 1998). However in a case at Point Farewell (east Van Diemen Gulf) the barricade was damaged in the first year of its construction and after subsequent repairs the creek eventually outflanked the barrage (Winn, 2001). Interestingly, following the barrage construction, *Melaleuca* regeneration did occur at a site of previous dieback. Although, Winn (2001) noted that it was unclear whether regeneration was due to the barrage reducing saltwater intrusion and/or higher than average rainfall that occurred after its construction. Regardless, the barrage was considered to have reduced landward extension of the tidal creek which is suggestive of reduced saltwater intrusion (Winn *et al.* 2006). Mulrennan & Woodroffe (1998) have also noted this to have occurred in other north Australian examples. Applegate (1999) has reported similar success in regenerating *Melaleuca* through use of barrages. Despite the potential benefits of barrages, there have been a number of issues related to barrage design and implementation in addition to numerous flow-on sedimentological, hydrological and ecological effects (Mulrennan & Woodroffe, 1998; Sterling, 1992). These will require thorough investigation and careful consideration before any possible implementation.

Understanding the life history stages susceptible to dieback is also important for ecological rehabilitation strategies, as this knowledge may allow for the development of age-specific restoration efforts (Ens & French, 2008). This study has suggested that different size classes may be affected by dieback at different floodplains. For example, the Gurrumuru "alive" quadrat showed no juvenile recruitment and some sickening of older trees, suggesting that that this site may be vulnerable to future dieback. The "dead" quadrat at Gurrumuru had the highest proportion of trees in the 5-10m size class, which coincides with Jimmy's statement about the older trees dying. If this trend continues, as it may do due to the observed sickness of some of the older trees, this may be detrimental for the site; especially in the face of a trigger event (Mueller-Dombois, 1988) such as a cyclone. It is possible that the lack of regeneration is related to feral animals, although this does not appear to be a straightforward relationship (see discussion on precipitating factors and Werner *et al.* 2006). Plant demography at Raymangirr is suggestive of an event that wiped out trees below 5m tall, followed by recent juvenile regeneration. However, Raymangirr "dead" quadrat showed the highest proportion of dead trees in the 5-10m size class, coinciding with higher salinity and feral animal impacts. If this is the case, older trees at Raymangirr "alive" may be resilient to dieback provided that feral animal impacts are kept low. Observing the recruitment of juvenile trees to the canopy at Raymangirr would therefore be a critical measure to denote an upward health trajectory at this site.

Dhuruputjpi "alive" appears to be a resilient site at present with healthy trees distributed evenly throughout the size classes. This quadrat also appears resilient to feral animal impacts, which requires further investigation as to the reasons for this. *Melaleuca* at the Buymarr "alive" quadrat were similar to the Gurrumuru "alive" quadrat as they were both dominated by tall trees (2-5m) with little juvenile recruitment. This may suggest difficulty for *Melaleuca* spp. to germinate or establish (Ens & French, 2008). The "dead" quadrat at Buymarr showed that shorter trees may have died off before taller trees, as some of the tall, sick trees had not yet suffered mortality. Bayapula "alive" provided an opportunity to visualise an intermediate state between healthy and dead stands. The dominance of shorter trees with worsening health as size class increased, suggested juvenile establishment may be followed by early mortality (Ens & French, 2008). In comparison, Bayapula "dead" displayed a mirror image size structure, suggesting that establishment had become inhibited which may have coincided with dieback of older trees.

Regarding size-specific rehabilitation (Ens & French, 2008) of these sites, at Gurrumuru and Buymarr "alive" quadrats, bypassing the size classes unable to establish by planting *Melaleuca* spp. over. 2m tall may provide a chance for *Melaleuca* to survive. Raymangirr and Dhuruputjpi will need to be monitored for changes in health and recruitment to the sites and size classes, but may not require planting. It is noted however, that the practicality of these approaches requires investigation.

With a view to ecological rehabilitation, there are other approaches that could be implemented to improve the chances of success. Due to the intraspecific variation in *Melaleuca* spp. (Niknam & McComb, 2000; Van der Moezel *et al.* 1991), it may be possible to collect seed from plants that are demonstrating salt tolerance in situ, and germinate them prior to planting (Marcar *et al.* 1999). Another approach is to undertake assisted evolution in glasshouses to breed salt tolerant plants (Niknam & McComb, 2000), though field survival has been demonstrably variable with this method (Marcar *et al.* 1999).

While MLRs did not consider soil pH a significant factor related to dieback, this study has identified sites (Gurrumuru and Buymarr) where acid sulfate soils are likely to be present. Oxidation of potential acid sulfate soils, often due to lowering of the ground water table (Stone *et al.* 1998), can result in extreme soil acidification (Hartikainen & Yli-Halla, 1985; Arkesteyn, 1980) causing serious impacts on vegetation (Ahearn *et al.* 1998; Inraratna *et al.* 1995). Considering that the results showed potential acid sulfate soils being located at very shallow depths in the soil profile (10 - 50 cm) (Tables 5 & 7; Figure 21), procedures involving large scale disturbance to the soil (for mechanical reclamation of micro-elevation or large scale digging for tree planting, etc.) should be approached with due caution.

# 5 Conclusions

Through synergy of ecological and socio-cultural information, the main findings of this collaborative two-way study were that *Melaleuca* spp. in Laynhapuy IPA are likely to have been predisposed to dieback by monospecificity (Archibald, 1995) and floodplain fringe ecotone dynamism (Cowie *et al.* 2000). Dieback may have initiated in earnest through the precipitating factors of salinity and feral impacts. In some areas this could have been exacerbated by cyclone events acting as a death trigger. Potential acid sulfate soils are likely at two floodplains (Gurrumuru and Buymarr) though MLRs conducted in this study suggest this was not statistically related to dieback.

While sea level rise is likely to be a major cause of saltwater intrusion (White *et al.* 2014; Steffan *et al.* 2009; Mulrennan & Woodroffe, 1998), feral ungulate (pig and buffalo) channels create a significant medium for saltwater to be transported from estuaries to floodplains (Bowman *et al.* 2010; Mulrennan & Woodroffe, 1998; Fogarty, 1982; Stocker, 1970), resulting in soil salinisation and ultimately *Melaleuca* dieback. Feral animals may also contribute to dieback directly through trampling and grazing. These conclusions were pre-empted by TOs with vast knowledge of their ancestral lands. The effects of salinity and ferals were quantified through ecological surveys and multiple linear regression models. Based on interviews with TOs there are more factors related to *Melaleuca* dieback that were beyond the scope of the ecological aspects of this study. Principally, these were: cyclone impacts, high tides and longer term rainfall. In addition, the spiritual aspects of TOs understandings regarding *Melaleuca* dieback are yet to be explored more deeply.

*Melaleuca* dieback was prevalent across coastal floodplains in Laynhapuy IPA and across *Melaleuca* species. At least three *Melaleuca* species are known to have been affected from ecological surveys (*M. acacioides, M. cajuputi, M. viridiflora*), with at least one more (*M. leucadendra*) suggested by a TO.

By working together using a two-way approach (Ens, 2012) both knowledge systems complemented one another. This was epitomised by Dhuruputjpi TO, Manman Wirrpanda, when he demonstrated his support for a two-way eco-cultural approach and his desire for this ecologically and culturally significant work to continue into the future; with Yolŋu knowledge and ŋapaki (non-Aboriginal) science working together:

> *'Somehow we can try to help each other to* [make a] *plan* [to] *come up balance same again…Yolŋu and ŋapaki balancing together. Doing the djama* [work].

Manman's willingness and desire for two-way eco-cultural research to continue on his land was a testament that the research was conducted in a respectful, inclusive and mutually beneficial manner which is considered a key outcome measure for success in cross-cultural research (Smith, 2012). Clearly there are more questions to be answered regarding *Melaleuca* spp. dieback, including the exploration of potential management responses, but the support of TOs is invaluable going forward given that the research was conducted on and for Aboriginal owned land and its people. Local support is a crucial factor in the continued success and mutual benefit of all future research projects in Laynhapuy IPA and other Aboriginal estates.

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# Appendices

**Appendix 1** – A few of the numerous Yolngu matha names for the species found in this study. Language names and moieties (in brackets where available) are included based on (1): (Yunupiŋu *et al.* 1995) and (2): Charles Darwin University's Yolŋu matha dictionary (Zorc *et al.* 2014).

| ***Melaleuca species*** | **Yolŋu matha names (moieties)** |
|---|---|
| ***Melaleuca viridiflora*** <br> **'Broad-leaved paperbark'** | D̲ind̲in (Dhuwa) (1,2) , D̲ar'man (Dhuwa)(2), Wurandaka (Dhuwa)(2), Rakala(') (Yirritja) (2), Bi[ipi[I (2), Barrukala (2), Ɖarinydjalk (2), Raŋan (2) |
| ***Melaleuca acacioides*** <br> **'Coastal paperbark'** | Gulun'kulun (Dhuwa) (1), (Yirritja) (2), Gulukulu' (2) |
| ***Melaleuca cajuputi*** <br> **'Cajeput tree'** | Nhami (Dhuwa)(1) Raŋan (Yirritja) (2), Badarr (Yirritja) (2), Munuy-munuy (Dhuwa) (2) Gurruwul (Dhuwa) (2) , n̲ämbarra(') (Dhuwa) (2), Barrukal (2), Djirri (2) |

**Appendix 2 –** Human ethics approval.

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**MACQUARIE**
University
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13 October 2015

Dr Emilie Ens
Department of Environmental Sciences
Faculty of Science and Engineering
Macquarie University
NSW 2109

Dear Dr Ens

**Reference No:** 5201500755

**Title:** *Eco-cultural impacts of saltwater intrusion in north-east Arnhem Land*

Thank you for submitting the above application for ethical and scientific review. Your application was considered by the Macquarie University Human Research Ethics Committee (HREC (Human Sciences & Humanities)) at its meeting on 25 September 2015 at which further information was requested to be reviewed by the HREC (Human Sciences and Humanities) Executive.

The requested information was received with correspondence on 4 October 2015. The HREC (Human Sciences and Humanities) Executive considered your responses at its meeting held on 13 October 2015.

I am pleased to advise that ethical and scientific approval has been granted for this project to be conducted at:

- Macquarie University

This research meets the requirements set out in the *National Statement on Ethical Conduct in Human Research* (2007 – Updated March 2014) (the *National Statement*).

This letter constitutes ethical and scientific approval only.

**Standard Conditions of Approval:**

1. Continuing compliance with the requirements of the *National Statement*, which is available at the following website:

http://www.nhmrc.gov.au/book/national-statement-ethical-conduct-human-research

2. This approval is valid for five (5) years, subject to the submission of annual reports. Please submit your reports on the anniversary of the approval for this protocol.

3. All adverse events, including events which might affect the continued ethical and scientific acceptability of the project, must be reported to the HREC within 72 hours.

4. Proposed changes to the protocol must be submitted to the Committee for approval before implementation.

It is the responsibility of the Chief investigator to retain a copy of all documentation related to this project and to forward a copy of this approval letter to all personnel listed on the project.

Should you have any queries regarding your project, please contact the Ethics Secretariat on 9850 4194 or by email ethics.secretariat@mq.edu.au

The HREC (Human Sciences and Humanities) Terms of Reference and Standard Operating Procedures are available from the Research Office website at:

http://www.research.mq.edu.au/for/researchers/how_to_obtain_ethics_approval/human_research_ethics

The HREC (Human Sciences and Humanities) wishes you every success in your research.

Yours sincerely

**Dr Karolyn White**
Director, Research Ethics & Integrity,
Chair, Human Research Ethics Committee (Human Sciences and Humanities)

This HREC is constituted and operates in accordance with the National Health and Medical Research Council's (NHMRC) *National Statement on Ethical Conduct in Human Research* (2007) and the *CPMP/ICH Note for Guidance on Good Clinical Practice*.

**Details of this approval are as follows:**

**Approval Date:** 13 October 2015

The following documentation has been reviewed and approved by the HREC (Human Sciences & Humanities):

| Documents reviewed | Version no. | Date |
|---|---|---|
| Macquarie University Ethics Application Form | 2.3 | July 2013 |
| Correspondence from DR Ens responding to the issues raised by the HREC (Human Sciences and Humanities) | | Received 4/10/2015 |
| MQ Participant Information and Consent Form (PICF) | 1 | 2/09/2015 |
| Saltwater Intrusion Questions | | |
| Macquarie University Appendix A: Research Involving Aboriginal and Torres Strait Islander People | | |

The following documentation was noted by the HREC (Human Sciences & Humanities):

| Documents noted | Date |
|---|---|
| Letter of Support from Yirralka Rangers, Laynhapuy Homelands Association Inc. | 10/09/2015 |

**Appendix 3** – Summary data. * Spp rich = species richness. Gnd cover = proportion ground cover. WDI = Wylie's dieback index. Rā̤kay = presence (+) or absence of Rā̤kay. Density^ = stems/ha. Recruits = juvenile recruitment presence (+) or absence (-). Mean pH 10 = mean pH at 10cm depth, minimum pH after 3 minutes given. Mean pH 50 = mean pH at 50cm depth, minimum pH after 3 minutes given. ** PASS = potential acid sulfate soils. ^^ = proportion feral damage. EC 10 = mean EC at 10cm depth. EC 50 = mean EC at 50cm depth. 10cm NaCl = NaCl at 10cm depth in parts per million (ppm). 50cm NaCl = NaCl at 50cm depth in parts per million (ppm). TO identified causes of dieback are the causes of *Melaleuca* spp. dieback identified by TOs. Positive (green) and negative (red) indicators of ecosystem health are coloured.

| | **Gurrumuru** | | **Raymangirr** | | **Dhuruputjpi** | | **Buymarr** | | **Bayapula** | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Alive | Dead | Alive | Dead | Alive | Dead | Alive | Dead | Alive | Dead |
| **Melaleuca spp** | cajuputi | cajuputi | viridiflora | viridiflora | cajuputi, viridiflora | viridiflora | acacioides | acacioides | acacioides | acacioides |
| **Spp rich** | 2 | 1 | 5 | 3 | 9 | 4 | 7 | 0 | 11 | 8 |
| **Gnd cover** | 0 | 0.247 | 0.71 | 0 | 0.088 | 0 | 0.343 | 0 | 0.28 | 0.092 |
| **WDI** | 1.2 | 4.93 | 1 | 4.86 | 1.46 | 5 | 1.14 | 4.65 | 2.79 | 4.76 |
| **Rā̤kay** | - | + | + | - | - | - | - | - | - | - |
| **Density^** | 500 | 750 | 900 | 1450 | 2800 | 625 | 1100 | 1300 | 6975 | 1875 |
| **Recruits** | - | - | + | - | + | - | + | - | + | - |
| **Mean pH 10** | 4.53 | 4.69 | 6.44 | 7.33 | 7.00 | 7.70 | 6.00 | 5.70 | 5.12 | 5.67 |
| **Mean pH 50** | 3.83 | 4.64 | 5.97 | 5.65 | 6.38 | 6.67 | 5.00 | 4.90 | 4.80 | 5.12 |
| **PASS 10**** | 3.63 | 4.55 | 5.90 | 5.45 | 6.32 | 5.83 | 4.15 | 4.29 | 4.88 | 5.42 |
| **PASS 50**** | 3.54 | 4.34 | 5.75 | 5.04 | 6.76 | 6.52 | 3.86 | 3.91 | 4.48 | 4.53 |
| **Ferals^^** | 0.14 | 0.454 | 0.29 | 0.505 | 0.25 | 0.777 | 0.071 | 0 | 0.034 | 0.214 |
| **EC 10** | 6.12 | 9.32 | 0.66 | 8.49 | 3.66 | 8.08 | 14.76 | 22.10 | 6.05 | 19.98 |
| **EC 50** | 6.52 | 11.55 | 2.55 | 3.90 | 4.67 | 4.10 | 10.68 | 13.97 | 7.41 | 14.77 |
| **10cm NaCl (ppt) mean (SE)** | 6.9 (0.264) | 10.395 (1.541) | 0.504 (0.213) | 9.578 (5.367) | 3.772 (0.195) | 8.913 (2.738) | 20.111 (2.018) | 28.505 (2.018) | 6.543 (3.35) | 22.413 (3.262) |