2019

Impacts of Cattle on the Vegetation Structure of Mangroves

Todd E. Minchinton
University of Wollongong, tminch@uow.edu.au

Hannah Shuttleworth
University of Wollongong

Justin Adam Lathlean
University of New South Wales, University of Wollongong, justinl@uow.edu.au

Russell McWilliam
University of Wollongong, ram923@uowmail.edu.au

Trevor Daly
New South Wales Department of Primary Industries

Publication Details

Minchinton, T. E., Shuttleworth, H. T., Lathlean, J. A., McWilliam, R. A. & Daly, T. J. (2019). Impacts of Cattle on the Vegetation Structure of Mangroves. Wetlands: the journal of the Society of Wetland Scientists, Online First 1-9.

Impacts of Cattle on the Vegetation Structure of Mangroves

Abstract
Across the globe coastal wetlands have been lost and degraded due to agriculture. Here we test hypotheses that there are differences in vegetation structure of the mangrove Avicennia marina at locations with or without cattle in the lower Shoalhaven River Estuary in New South Wales, Australia. We sampled the pneumatophores, seedlings, saplings, and trees within the mangrove forest and landward of the forest where cattle are most active. Areas with cattle had fewer trees, and their lowest branches were more than 2 m above the ground, giving trees an umbrella-shaped morphology. Although abundances of saplings and seedlings were highly variable among locations, plants at both stages were shortest along the landward side of the forest in the presence of cattle and seedlings were bushier, suggesting consumption of the apical shoots. A reduction in pneumatophore density and the highest proportion of branched pneumatophores occurred along the landward side of the forest in the presence of cattle, indicating impacts of trampling. Prospects for regeneration of the mangroves in the presence of cattle appear limited due to grazing, physical disturbance and trampling across multiple life history stages. Livestock paddocks should be fenced to exclude cattle and prevent degradation of these coastal intertidal habitats.

Publication Details
Minchinton, T. E., Shuttleworth, H. T., Lathlean, J. A., McWilliam, R. A. & Daly, T. J. (2019). Impacts of Cattle on the Vegetation Structure of Mangroves. Wetlands: the journal of the Society of Wetland Scientists, Online First 1-9.

Impacts of Cattle on the Vegetation Structure of Mangroves

Todd E. Minchinton[1,*], Hannah T. Shuttleworth[1], Justin A. Lathlean[1], Russell A. McWilliam[1], Trevor J. Daly[2]

[1]Centre for Sustainable Ecosystem Solutions and School of Earth, Atmospheric and Life Sciences, University of Wollongong, New South Wales 2522, Australia

[2]New South Wales Department of Primary Industries, PO Box 17, Batemans Bay, New South Wales 2536, Australia

*Corresponding author: Dr Todd E. Minchinton, School of Earth, Atmospheric and Life Sciences, University of Wollongong, NSW 2522, Australia. Tel: +61 (2) 4221 5188; Fax: +61 (2) 4221 4135

Email: tminch@uow.edu.au; ORCID 0000-0001-6989-9315

Hannah T. Shuttleworth: hshuttleworth@gmail.com

Justin A. Lathlean: jlathlean@gmail.com

Russell A. McWilliam: ram923@uowmail.edu.au

Trevor J. Daly: trevor.daly@dpi.nsw.gov.au

Abstract

Across the globe coastal wetlands have been lost and degraded due to agriculture. Here we test hypotheses that there are differences in vegetation structure of the mangrove *Avicennia marina* at locations with or without cattle in the lower Shoalhaven River Estuary in New South Wales, Australia. We sampled the pneumatophores, seedlings, saplings, and trees within the mangrove forest and landward of the forest where cattle are most active. Areas with cattle had fewer trees, and their lowest branches were more than 2 m above the ground, giving trees an umbrella-shaped morphology. Although abundances of saplings and seedlings were highly variable among locations, plants at both stages were shortest along the landward side of the forest in the presence of cattle and seedlings were bushier, suggesting consumption of the apical shoots. A reduction in pneumatophore density and the highest proportion of branched pneumatophores occurred along the landward side of the forest in the presence of cattle, indicating impacts of trampling. Prospects for regeneration of the mangroves in the presence of cattle appear limited due to grazing, physical disturbance and trampling across multiple life history stages. Livestock paddocks should be fenced to exclude cattle and prevent degradation of these coastal intertidal habitats.

Key words: *Avicennia marina*, grazing, herbivory, recruitment, saltmarsh, trampling

Introduction

Across the globe mangrove forests and other coastal wetlands are under particular threat of habitat loss from mariculture and urbanisation (Spalding et al. 1997; Valiela et al. 2001; Alongi 2002; Lee et al. 2006), but the threat of agriculture, and specifically livestock grazing, has received relatively little attention despite rapidly growing food production with expanding human populations and the often obvious impacts on the plants themselves (e.g. Bridgewater and Cresswell 1999; Dahdouh-Guebas et al. 2006; Hoppe-Speer et al. 2015; He and Silliman 2016; Kauffman et al. 2016). Although mangrove loss has been primarily linked to agriculture through land clearing (e.g. Abuodha and Kairo 2001), degradation of mangrove ecosystems can occur indirectly through use of adjacent land for livestock farming or directly through use of mangrove forests and saltmarsh as paddocks for grazing, movement and resting of livestock (He and Silliman 2016; Wood et al. 2017).

In riparian and terrestrial habitats, it is widely recognised that livestock farming can have substantial impacts on the biotic, geomorphic, and hydrological environment (Wilson 1990; Trimble and Mendel 1995; Belsky et al. 1999; Robertson and Rowling 2000). Habitat damage due to livestock in riparian ecosystems is particularly concentrated (e.g. Fleischner 1994), and it thus might be predicted that impacts due to cattle grazing and trampling in the unconsolidated sediments of estuarine habitats might be substantial (Fouda and Ali-Muharrami 1995). Although there is a relatively long history of studies examining the impacts of grazing in salt marshes (Ranwell 1961; Reimold et al. 1975; Bakker 1985; Andresen et al. 1990; Levin et al. 2002; Di Bella et al. 2014), comparatively little is known about the direct and indirect effects of livestock on mangrove forests (e.g. Dahdouh-Guebas et al. 2006; He and Silliman 2016). In coastal saltmarsh habitats grazing and trampling by sheep, cattle, and horses can reduce the abundance and diversity of plants (e.g. Jensen 1985; Turner 1987; Tessier et al. 2003). For example, Zedler et al. (1995), working in temperate

Australian saltmarshes, proposed that depressions in the soil created by cattle trampling might alter plant community composition by favouring species more suited to edaphic conditions under this disturbance agent. Observations of grazing on mangroves have been recorded for a diverse range of species (e.g. camels: Fouda and Al-Muharrami 1995; cattle: Yang et al. 2014; sheep: Hogarth 1999; goats: Hoppe-Speer et al. 2015; wallabies and kangaroos: Hutchings and Saenger 1987; pigs: Hoppe-Speer et al. 2015; water buffalo: Dahdouh-Guebas et al. 2006), and mangrove leaves have been considered as cattle feed (see Morton 1965). The relatively few investigations of impacts of livestock in mangroves have noted the fragmentation of forests due to the creation of pathways, alterations to vegetation structure, and changes to soil conditions (Dahdouh-Guebas et al. 2006; Yang et al. 2014; Hoppe-Speer et al. 2015).

In Australia, cattle have been recognised as a significant agent of disturbance at land-water interfaces in riparian habitats (Jansen and Robertson 2001). Along the coast of New South Wales (NSW), Australia, it is common for saltmarsh to have been cleared for conversion to pasture or used directly for grazing (Adam 2002; Daly 2013). In the lower Shoalhaven River estuary, NSW, extensive areas of coastal land have been cleared for dairy farming (Umwelt 2005, 2006), with pasture often leading directly into the intertidal landscape comprised of a complex of open mud, saltmarsh and mangroves. Many paddocks are left unfenced to give cattle access to saltmarsh and mangroves as a source of water, forage, and shade (Umwelt 2005, 2006). Consequently, livestock activity associated with coastal dairy farming has been identified as a significant factor contributing to the loss of ecologically important saltmarsh (Coast Saltmarsh is listed as an Endangered ecological community under the NSW Biodiversity Conservation Act 2016 and Subtropical and Temperate Coastal Saltmarsh is listed as a Vulnerable ecological community under the Commonwealth Environment Protection and Biodiversity Conservation Act 1999 in Australia) and mangrove habitat

(Marine Vegetation, including mangroves and saltmarsh plants) has been protected under the NSW Fisheries Management Act 1994) (see Daly 2013).

The aim of our investigation was to assess the damage to mangrove vegetation associated with unrestricted cattle access to mangrove forests in the lower Shoalhaven River estuary. We quantified differences in the vegetation structure across multiple life history stages (trees, saplings, seedlings) and structural elements (size, branches, leaves, roots) of the mangrove *Avicennia marina* at locations with or without cattle. At each location we focused on two key zones across the intertidal landscape with differential activity of cattle: within the mangrove forest where cattle are less active and along the landward side of the forest between the mangroves and the pasture where cattle are most active. We thus predicted that mangrove vegetation would be most heavily impacted along the landward side of the mangrove forest at locations with cattle. Our approach documenting impacts across the various life history stages will help to identify which life history stage and demographic process might limit forest regeneration and thus guide effective conservation strategies for these protected estuarine habitats.

Methods

Region and locations studied

The study was done from June to August (winter) of 2006 in mangrove forests of the lower Shoalhaven River estuary (34°52′30″ S, 150°42′50″ E), east of Nowra on the south coast of NSW, Australia. The estuary extends from Nowra Bridge to Shoalhaven and Crookhaven Heads and has a catchment area of 21 km^2 with an extensive floodplain (Umwelt 2005, 2006). The intertidal landscape in the estuary is comprised of mangrove forests fringing the rivers, and saltmarshes bordering the landward sides of the mangrove forests. The majority of land is zoned for agriculture and used for dairy farming. Clearing for agriculture and extensive erosion of the riverbanks has substantially reduced the area of estuarine vegetation: the remaining mangroves and saltmarsh vegetation covers areas of 3.5 km^2 and 1.5 km^2, respectively (Umwelt 2005, 2006).

Four locations with mangrove forests were chosen along the lower Shoalhaven River estuary: two locations (Regatta Island, Ryan's Creek) were private dairy farming properties where cattle had unrestricted access to mangroves due to the absence of fencing, and two (Berry's Bay, Comerong Island) were control (or reference) locations that, to our knowledge, have never and certainly not within decades been accessed by cattle. Locations were spatially independent and separated by at least 2 km. The mangrove forests in the region are comprised of two tree species which are both approaching their global southern range limits: the larger *A. marina* and the smaller *Aegiceras corniculatum*, but *A. marina* is the dominant species. At locations with cattle present, saltmarsh vegetation landward of the mangrove forest was severely degraded, with cover restricted to small and isolated patches of the grass *Sporobolus virginicus*, the chenopods *Suaeda australis* and *Sarcocornia quinqueflora*, the native rush *Juncus kraussii* and the non-indigenous, invasive rush *J. acutus* (see Harvey et al. 2010).

Regatta Island was converted into a dairy farm in the early 1900s and is a fourth-generation dairy farm. The landward-facing edge of the island forms a protected inlet with the mainland. Along this edge, the upper paddocks of the farm have been fenced off from cattle and have dense mangroves. The lower paddocks of the farm, where the study was done, are not fenced and mangroves are noticeably less dense. In these lower paddocks a permanent population of 20 to 25 heifers are rotated through daily for grazing. Ryan's Creek is a permanent agistment and the number of cattle present is variable. At the time of sampling there were 15 head of cattle rotating through the paddocks. Importantly, at both of these locations the cattle are rotated through relatively small paddocks (estimated at roughly 0.12 to 0.14 km^2 including the intertidal landscape, but the area used is variable and calculating an accurate long-term stocking rate is not possible), with mangrove forest extending roughly 400 m alongshore, and thus there is the potential for substantial impact. In each paddock, cattle have access to pasture, which transitions into the intertidal landscape dominated by patches of saltmarsh vegetation and then mangroves with an intertidal extent ranging from 50 m to 100 m. At both locations, cattle roamed throughout the intertidal landscape and were observed walking and resting in and along the landward side of the mangrove forests, as well as consuming mangrove vegetation (B. Coulthart personal communication; H. Shuttleworth personal observation).

The location at Comerong Island was at the northern part of the island in the Comerong Island Nature Reserve, created in 1986. At this location the intertidal landscape is comprised from seaward to landward of mangrove forest, saltmarsh and then swamp-oak forest dominated by *Casuarina glauca*. The location at Berry's Bay was on Crown Land and more impacted by humans than the Comerong Island location: some of the upper saltmarsh had been claimed as private land and there was evidence of illegal dumping of rubbish, but sampling was not done in these disturbed areas. At both locations, an area with mangrove forest extending roughly 400 m alongshore was selected, to parallel the alongshore extent of the locations with cattle.

Sampling design

At each of the four locations, a sampling area with mangrove forest extending 150 to 200 m alongshore was selected to occupy the central area at the location. This area was divided into two intertidal zones: one within the upper (or landward) part of the mangrove forest (the lower part of the mangrove forest adjacent to the river was not used) and one along the landward edge of the forest where there is a complex of open mud, mangroves and patches of saltmarsh vegetation. These zones were delineated by the boundary where the mangrove forest with complete canopy cover transitions landward to a mud, mangrove and saltmarsh complex. To ensure comparable areas were being sampled among locations, tidal heights were used to determine zonal boundaries, and this was done by measuring water depth along the landward edge of the forest at each location during specific times of the tidal cycle. These two zones were also distinguished because cattle roaming the intertidal landscape occurred more frequently and were more active along the landward side of the mangrove forest than within the mangrove forest where there are more trees and mud is less consolidated (B. Coulthart personal communication; H. Shuttleworth personal observation). Although cattle activity could not be quantified outside of personal observations, we nevertheless predicted that not only would there be differences between locations with or without cattle, but that these differences would be more pronounced along the landward edge of the mangroves than within the mangrove forest.

At each location, two sites were selected in each of the two zones, and each site covered 10 m of intertidal extent and stretched 50 m alongshore, giving a sampling area of 500 m^2 for each site and 2000 m^2 for each location. Sites were separated by at least 15 m and positioned where there was sufficient intertidal extent for sampling and away from areas with obvious disturbance that changed the nature of the sampling area. Sites within the mangrove forest (referred to as “mangrove forest”) were located in upper part of the forest, and extended 10 m seaward from the landward edge of the mangrove forest. Sites along the edge of the mangrove forest (referred to as “mangrove edge”) extended 10 m landward from the landward edge of the mangrove forest. To account for edge effects, a 5 m band running along the forest boundary and separating these two zones was excluded from sampling.

Sampling variables

Cattle may directly impact *A. marina* and its capacity for persistence and regeneration through trampling, other physical disturbance (e.g. breakage of branches) and grazing effects. To assess these potential effects, mangrove vegetation was quantified by measuring the production of aboveground roots (i.e. pneumatophores) and the sizes of individual plants across various life history stages (trees, saplings, seedlings). Trees were classified as individuals >150 cm tall and with a crown >1 m^3, saplings as individuals up to 150 cm tall with lateral branches but not forming canopy, and seedlings as single-stemmed individuals ≤ 50 cm tall (see Clarke and Allaway 1993; Minchinton 2001). Plants > 50 cm tall almost always had lateral branches. Classification of trees and saplings is difficult, however, because size and life history stage are not necessarily correlated. For example, short plants with thick trunks would be classified as saplings, but these apparently stunted plants appear much older and may be capable of reproducing.

Aboveground root production was measured by the densities and heights of pneumatophores. At each site, the densities of live pneumatophores were estimated by counting their numbers in ten, 1 m^2 (1 m × 1 m) randomly located quadrats. A separate record was kept of the number that were branched, an indicator of damage from trampling in mangrove habitats (see Ross 2006). Some pneumatophores had characteristic assemblages of epiphytic algae (see King and Wheeler 1984), but the occurrence of these algae was sporadic and not quantified. In each quadrat, the heights of five randomly selected unbranched pneumatophores were measured from their bases at the mud surface to their tips. Seedling densities were estimated in ten, 2 m^2 (1 m × 2 m) quadrats in each site. The heights and numbers of leaves for 50 randomly selected seedlings were quantified across these quadrats. The heights of seedlings were measured from the base of the stem at the mud surface to the tip of the stem. Sapling and tree densities were estimated in two, 100 m^2 (10 m × 10 m) randomly selected quadrats in each site. The height of 20 randomly selected saplings, measured from the base of the trunk at mud surface to top of the plant, was recorded in each site. The sizes of trees were estimated by measuring circumference (or girth, G) of their central stems (or trunks) at 130 cm above the ground (G_{130}) for (where available) 20 randomly selected trees at each site (Brokaw and Thompson 2000). Trees had relatively straight, single-stemmed trunks and, consequently, we did not encounter the problem associated with estimating tree girth for multiple-stemmed mangrove trees (see Dahdouh-Guebas and Koedam 2006). On each tree, the height of the lowest branch was used as an indicator of consumption and physical disturbance of mangrove vegetation by cattle, and this was measured as the vertical distance from the base of the trunk at the mud surface to the base of the lowest branch with live foliage (i.e. excluding dead branches).

Statistical analyses

A three-factor, nested analysis of variance (ANOVA) was used to determine differences in the effect of cattle (fixed factor: present, absent), zone (fixed factor: mangrove forest, mangrove edge) and location (random factor nested within cattle treatments) for each of the sampling variables. For each sampling variable, the mean value of estimates was calculated for each site. These means for each site were then used as replicates (n=2 sites for each zone at each location) in the ANOVA. Following significant cattle by zone interactions in ANOVA, Student-Newman Keuls (SNK) multiple comparisons tests were done to determine the location of differences among these four treatments. Data were transformed as necessary to reduce variance heterogeneity (see Table 1). There were no trees at one site at Regatta Island and, therefore, to balance the design we used G_{130} and lowest branch height of the other site and reduced the degrees of freedom in the residual by one (Quinn and Keogh 2002).

Results

There were stark differences in the vegetation structure of *A. marina* in the presence of cattle and, as predicted, these were most pronounced along the landward side of the mangrove forest where cattle are most active. Throughout the intertidal landscape there were substantially fewer trees where cattle were present (Fig. 1a, Table 1a). Within the mangrove forest, almost twice as many trees occurred in the absence than in the presence of cattle, and this difference was most pronounced along the landward edge of the forest where trees were scarce (< 5 per 100 m^2) (Fig. 1a, b). Nevertheless, trees on the landward side of the forest with cattle were approximately double the girth of those in the mangrove forest, whereas the reverse pattern was evident in the absence of cattle (Fig. 1b, Table 1b). There were also striking differences in tree morphology: where cattle were present the lowest tree branches were at least 2 m above the ground, likening their shape to an open umbrella, whereas in the absence of cattle branches were on average only 34 cm above the mud (Fig. 1c, Table 1c).

Densities of saplings were highly variable among locations, primarily due to extremely few saplings at Ryan's Creek where cattle were present, and saplings were at greater densities along the landward side than within the mangrove forest (Fig. 1d, Table 1d). Saplings were, however, consistently shorter in the presence than in the absence of cattle and shortest along the edge of the mangrove forest with cattle present, particularly at Regatta Island where saplings appeared stunted (Fig. 1e, Table 1e).

The abundance of seedlings, like saplings, was extremely variable among locations, with large numbers at Comerong Island and few at Ryan's Creek (Fig. 1d, f, Table 1f). Nevertheless, seedlings were consistently taller in the mangrove forest than along its landward edge (Fig. 1g, Table 1g). In general, at both locations with cattle, seedlings were least abundant and shortest along the landward side of the forest, and these short seedlings had the greatest numbers of leaves compared to similar areas in the absence of cattle and in the mangrove forest in the presence of cattle (Fig. 1f, g, h, Table 1f, g, h).

Areas where cattle roamed the landward side of the mangrove forest were associated with prominent differences in the abundance and morphology of pneumatophores (i.e. aerial roots) compared to all other areas. Along the edge of the forest, there were on average six times more pneumatophores and proportionally fewer branched pneumatophores in the absence than in the presence of cattle, although pneumatophore heights were similar (Fig. 1i, j, k, Table 1i, j, k). Moreover, at locations with cattle, areas along the landward side of the forest had fewer pneumatophores and these were shorter and more branched than in the mangrove forest (Fig. 1i, j, k, Table 1i, j, k). In contrast, within the mangrove forest the density and percentage of pneumatophores that were branched was similar in the presence or absence of cattle, although pneumatophores were taller in areas with cattle (Fig. 1i, j, k, Table 1i, j, k).

Discussion

There were dramatic differences in the vegetation structure of *A. marina* between areas with or without cattle, providing strong evidence for direct impacts of grazing and trampling by cattle in the mangrove environment. Although experimental manipulation of cattle would be needed to attribute causal links, observations of cattle trampling pneumatophores and consuming mangrove leaves coupled with the conspicuous and unusual differences in morphology of trees, saplings and pneumatophores provide compelling evidence of the impacts of cattle (see He and Silliman 2016).

Trees were dramatically reduced in abundance at both locations with cattle, and the few and more isolated trees on the landward side of the mangrove forest were large and mature individuals, that were shaped like open umbrellas with the lowest branches and canopy consistently 2 m above the substratum. Fewer trees likely translate to a loss of production and associated carbon storage (Kauffman et al. 2016). This tree morphology reflects the height at which cattle can consume leaves and cause physical damage to lower branches, and others have observed similar characteristic grazing lines within mangrove forests (e.g. Hoppe-Speer et al. 2015). This altered morphology was also obvious in the mangrove forest with cattle present, although more variable among trees, suggesting that cattle graze mangroves in the upper part of the forest but do not have as large an impact on tree abundance as on the landward side. This loss in structural complexity of the mangrove trees might negatively influence a diverse array of taxa that depend on mangroves for shelter, nesting and food.

Saplings showed similar results to trees, with reduced densities in the presence of cattle, but only at Ryan's Creek. Along the landward side of the forest at both locations with cattle, but particularly at Regatta Island, the majority of saplings appeared stunted and old, with thick trunks and short branches with compact foliage and tightly clustered leaves around the central stem, likely reflecting suppression of growth and morphological changes due to sustained grazing of apical shoots (e.g. Dahdouh-Guebas et al. 2006). At Ryan's Creek some plants had unusual morphology indicative of cattle grazing, with long elongated central stems with clumps of leaves at heights > 1.7 m (as well as low to the ground), resembling lollipops. It thus appears that grazing by cattle was reducing the abundance and size of saplings, preventing their transition into trees.

Similar to patterns of abundance for trees, there were few seedlings in areas with cattle along the landward side of the mangrove forest (Hoppe-Speer et al. 2015). Trampling by livestock in saltmarshes has been shown to reduce establishment of seedlings due to a loss in soil structure increasing the likelihood of small marsh plants being uprooted (Jensen 1985; Turner

1987; Tessier et al. 2003; Wasson and Woolfolk 2011). In addition to trampling, cattle were also likely grazing on mangrove seedlings because, similar to the stunting of saplings, they were shorter and had more leaves in these areas, suggesting a compensatory response to breakage of the apical shoot (Strauss and Agrawal 1999). Alternatively, limited natural production or supply of propagules to this area or unfavourable soil conditions might have reduced seedling establishment (e.g. Minchinton 2001). Unravelling these multiple explanations requires further testing. Regardless, in areas with cattle present there were few seedlings available for forest regeneration.

The small number of pneumatophores along the landward edge of the forest is likely associated with the scarcity of trees in this area coupled with trampling by cattle. Studies have shown that trampling by humans can bend, break and eventually detach pneumatophores (Skilleter 1996; Ross 2006), and cattle are likely having similar effects. Indeed, reductions in abundance and branching of pneumatophores have been linked to increased human disturbance and an indicator of trampling disturbance in mangrove forests (see Skilleter 1996; Ross 2006), and the percentage of branched pneumatophores was greatest in these landward regions with cattle. Reduced abundance and increased deformity of aerial roots may diminish the capacity of mangrove saplings and trees to exchange gases in physiologically stressful low oxygen environments, trap sediments and prevent coastal erosion, and provide habitat for epiphytic macroalgae and associated gastropods (e.g. Skilleter and Warren 2000; Chapman et al. 2005).

There appears extremely limited capacity for mangrove regeneration along the landward side of forest because while cattle remain in these relatively small paddocks there will be sustained impacts (Wasson and Woolfolk 2011). Indeed, all life history stages of the mangrove *A. marina* appeared influenced by cattle access and grazing. The scarcity of seedlings along the landward edge of the forest at both locations and the lack of saplings at Ryan's Creek suggest that establishment of seedlings or successful transition to the sapling stage due to consumption or trampling by cattle are limiting demographic processes. Importantly, seedlings with cotyledons attached were present, indicating that there is at least some dispersal of propagules into these areas and suggesting that edaphic conditions remain suitable for establishment (Minchinton 2006). Nevertheless, dispersal of *A. marina* is often highly localised (e.g. Clarke 1993) and the presence of few mature trees along the landward side of the mangrove forest indicates that there might be limited prospects for natural forest regeneration from local populations (Robertson and Rowling 2000). Seedlings that made the transition into saplings, such as those at Regatta Island, were stunted, suggesting suppression of growth by grazing cattle. Consequently, the continued presence of cattle, even at reduced stocking densities, is likely to prevent natural regeneration of the mangrove vegetation along the landward side of mangrove forests.

Assuming that tidal levels and hydrodynamic and edaphic conditions are suitable for natural regeneration, as appears to be the case, fencing to exclude cattle access should promote natural regeneration of these areas by eliminating the direct impacts of grazing and trampling (see Fleischner 1994, Dahdouh-Guebas et al. 2006), particularly for mangrove *A. marina* which is generally a robust and resilient mangrove species. The influence of fencing on the indirect effects of cattle living in paddocks adjacent to coastal waterways, such as potential impacts of elevated sedimentation and nutrients, cannot be predicted, but investigations in riparian habitats highlight positive changes to water quality and sedimentation among other parameters (Belsky et al. 1999; Sovell et al. 2000). Natural regeneration of mangroves under such disturbance conditions is predicted to be slow (e.g. Ross 2006), particularly due to limitations on recruitment, but planting of *A. marina* seedlings would accelerate this process and has already proven successful in this catchment by members of Shoalhaven Riverwatch.

Fencing provides benefits to farmers by preventing stock losses (e.g. when cattle get stuck in the mud), reducing land erosion and thus improving land value (Staton and O’Sullivan 2006). At a minimum, fencing should aim to regenerate the interconnected mangrove, saltmarsh and swamp oak forest complex across the coastal landscape, protecting listed Endangered Ecological Communities and Marine Vegetation (Daly 2013). Once cattle are excluded, monitoring forest regeneration, including habitat structure, associated biota, as well as changes to edaphic and hydrodynamic conditions, would inform future conservation strategies by quantifying the speed and full extent of mangrove regeneration.

Acknowledgements

Foremost we thank the farmers, Bruce Coulthart and Paul Wallace, who allowed access to their properties and shared decades of ecological insights acquired by living next to mangrove forests. We are also particularly grateful to Charlie Weir of Shoalhaven Riverwatch for helping to find suitable field locations, organising access to private property, and sharing his ecological knowledge of the Shoalhaven region. Ray Massie of Shoalhaven Council generously provided aerial photos of study locations. Thanks to Mels Manns, Marta Marchwicka, Kael Shuttleworth, and Scott Shuttleworth for assistance in the field. Comments on the research by Peter Clarke, Ana Gracanin, and Ron West were helpful and appreciated. Funding was provided by New South Wales Department of Primary Industries and the Centre for Ecosystem Solutions at the University of Wollongong.

References

Abuodha PAW, Kairo JG (2001) Human-induced stresses on mangrove swamps along the Kenyan coast. Hydrobiologia 458:255–265

Adam P (2002) Saltmarshes in a time of change. Environmental Conservation 29:39–61

Alongi DM (2002) Present state and future of the world's mangrove forests. Environmental Conservation 29:331–349

Andersen H, Bakker JP, Brongers M, Heydemann B, Irmler U (1990) Long-term changes of salt marsh communities by cattle grazing. Vegetatio 89:137–148

Bakker JP (1985) The impact of grazing on plant communities, plant populations and soil conditions on salt marshes. Vegetatio 62:391–398

Belsky AJAJ, Matzke A, Uselman S (1999) Survey of livestock influences on stream and riparian ecosystems in the western United States. Journal of Soil and Water

Conservation 54:419–431

Bridgewater PB, Cresswell ID (1999) Biogeography of mangrove and saltmarsh vegetation: Implications for conservation and management in Australia. Mangroves and Salt Marshes 3:117–125

Brokaw N, Thompson J (2000) The H for DBH. Forest Ecology and Management 129:89–91

Chapman MG, Michie K, Lasiak T (2005) Responses of gastropods to changes in amounts of leaf litter and algae in mangrove forests. Journal of the Marine Biological Association of the United Kingdom 85:1481–1488

Clarke PJ (1993) Dispersal of grey mangrove (Avicennia marina) propagules in southeastern Australia. Aquatic Botany 45:195–204

Clarke PJ, Allaway WG (1993) The regeneration niche of the grey mangrove (Avicennia marina): effects of salinity, light and sediment factors on establishment, growth and survival in the field. Oecologia 93:548–556

Dahdouh-Guebas F, Koedam N (2006) Empirical estimate of the reliability of the use of the Point-Centred Quarter Method (PCQM): Solutions to ambiguous field situations and description of the PCQM+ protocol. Forest Ecology and Management 228:1–18

Dahdouh-Guebas F, Vrancken D, Ravishankar T, Koedam N (2006) Short-term mangrove browsing by feral water buffalo: Conflict between natural resources, wildlife and subsistence interests. Environmental Conservation 33:157–163

Daly T (2013) Coastal saltmarsh. Primefact. New South Wales Department of Primary Industries, Australia. Reference number 11473

Di Bella CE, Jacobo E, Golluscio RA, Rodríguez AM (2014) Effect of cattle grazing on soil salinity and vegetation composition along an elevation gradient in a temperate coastal salt marsh of Samborombón Bay (Argentina). Wetlands Ecology and Management 22:1–13

Fleischner TL (1994) Ecological Costs of Livestock Grazing in Western North America. Conservation Biology 8:629–644

Fouda MM, Ali-Muharrami M (1995) An initial assessment of mangrove resources and human activities at Mahout Island, Arabian Sea, Oman. Hydrobiologia 295:353–362

Harvey KJ, Britton DR, Minchinton TE (2010) Insect diversity and trophic structure differ on native and non-indigenous congeneric rushes in coastal salt marshes. Austral Ecology 35:522–534

He Q, Silliman BR (2016) Consumer control as a common driver of coastal vegetation worldwide. Ecological Monographs 86:278–294

Hogarth PJ (1999) The biology of mangroves. Oxford University Press, Oxford

Hoppe-Speer SCL, Adams JB, Bailey D (2015) Present state of mangrove forests along the Eastern Cape coast, South Africa. Wetlands Ecology and Management 371–383

Hutchings P, Saenger P (1987) Ecology of mangroves. University of Queensland Press, St Lucia

Jansen A, Robertson AI (2001) Relationships between livestock management and the ecological condition of riparian habitats along an Australian floodplain river. Journal of Applied Ecology 38:63–75

Jensen A (1985) The effect of cattle and sheep grazing on salt-marsh vegetation at Skallingen, Denmark. Vegetatio 60:37–48

Kauffman JB, Hernandez Trejo H, del Carmen Jesus Garcia M, Heider C, Contreas WM (2016) Carbon stocks of mangroves and losses arising from their conversion to cattle pastures in the Pantanos de Centla, Mexico. Wetlands Ecology and Management 24:203–216

King RJ, Wheeler MD (1984) Composition and geographic distribution of mangrove macroalgal communities in New South Wales. Proceedings of The Linnean Society of

New South Wales 108:97–117

Lee SY, Dunn RJK, Young RA, Connolly RM, Dale PER, Dehayr R, Lemckert CJ, McKinnon S, Powell B, Teasdale PR, Welsh DT (2006) Impact of urbanization on coastal wetland structure and function. Austral Ecology 31:149–163

Levin PS, Ellis J, Petrik R, Hay ME (2002) Indirect effects of feral horses on estuarine communities. Conservation Biology 16:1364–1371

Minchinton TE (2001) Canopy and substratum heterogeneity influence recruitment of the mangrove Avicennia marina. Journal of Ecology 89:888–902

Minchinton TE (2006) Consequences of pre-dispersal damage by insects for the dispersal and recruitment of mangroves. Oecologia 148:70–80

Morton JF (1965) Can the red mangrove provide food, feed and fertilizer? Economic Botany 19:113–123

Quinn G, Keogh M (2002) Experimental design and data analysis for biologists. Cambridge University Press, Cambridge

Ranwell D. (1961) Spartina salt marshes in southern England: 1. The effects of sheep grazing at the upper limits of Spartina marsh in Bridgwater Bay. Journal of Ecology 49:325–340

Reimold RJ, Linthurst RA, Wolf PL (1975) Effects of grazing on a salt marsh. Biological Conservation 8:105–125

Robertson AI, Rowling RW (2000) Effects of livestock on riparian zone vegetation in an Australian dryland river. Regulated Rivers: Research and Management 16:527–541

Ross PM (2006) Macrofaunal loss and microhabitat destruction: The impact of trampling in a temperate mangrove forest, NSW, Australia. Wetlands Ecology and Management 14:167–184

Skilleter GA (1996) Validation of rapid assessment of damage in urban mangrove forests and relationships with molluscan assemblages. Journal of the Marine Biological Association of the United Kingdom 76:701

Skilleter GA, Warren S (2000) Effects of habitat modification in mangroves on the structure of mollusc and crab assemblages. Journal of Experimental Marine Biology and Ecology 244:107–129

Sovell LA, Vondracek B, Frost JA, Mumford KG (2000) Impacts of rotational grazing and riparian buffers on physicochemical and biological characteristics of Southeastern Minnesota, USA, streams. Environmental Management 26:629–641

Spalding MD, Blasco E, Field CD (1997) World mangrove atlas. The International Society for Mangrove Ecosystems, Okinawa

Staton J, O'Sullivan J (2006) Stock and waterways: A manager's guide. Land and Water Australia, Canberra

Strauss SY, Agrawal AA (1999) The ecology and evolution of plant tolerance to herbivory. Trends in Ecology and Evolution 14:179–185

Tessier M, Vivier J-P, Ouin A, Gloaguen JC, Lefeuvre JC (2003) Vegetation dynamics and plant species interactions under grazed and ungrazed conditions in a western European salt marsh. Acta Oecologica 24:103–111

Trimble SW, Mendel AC (1995) The cow as a geomorphic agent - A critical review. Geomorphology 13:233–253

Turner MG (1987) Effects of grazing by feral horses, clipping, trampling, and burning on a Georgia salt marsh. Estuaries 10:54–60

Umwelt (Australia) Pty Limited (2005) Shoalhaven River estuary data compilation study

Umwelt (Australia) Pty Limited (2006) Shoalhaven River estuary management plan

Valiela I, Bowen JL, York JK (2001) Mangrove Forests: One of the World's Threatened Major Tryopical Environments. BioScience 51:807

Wasson K, Woolfolk A (2011) Salt marsh-upland ecotones in central California: Vulnerability to invasions and anthropogenic stressors. Wetlands 31:389–402

Wilson AD (1990) The effect of grazing on Australian ecosystems. Proceeding of the Ecological Society of Australia 16:235–244

Winer BJ, Brown DR, Michels KM (1991) Statistical principles in experimental design. McGraw-Hill, Inc., New York

Wood KA, O'Hare MT, McDonald C, Searle KR, Daunt F, Stillman RA (2017) Herbivore regulation of plant abundance in aquatic systems. Biological Reviews 92: 1128–1141

Yang SC, Riddin T, Adams JB, Shih SS (2014) Predicting the spatial distribution of mangroves in a South African estuary in response to sea level rise, substrate elevation change and a sea storm event. Journal of Coastal Conservation 18:459–469

Zedler J., Nelson P, Adam P (1995) Plant community organization in New South Wales saltmarshes: species mosaics and potential causes. Wetlands (Australia) 14:1–18

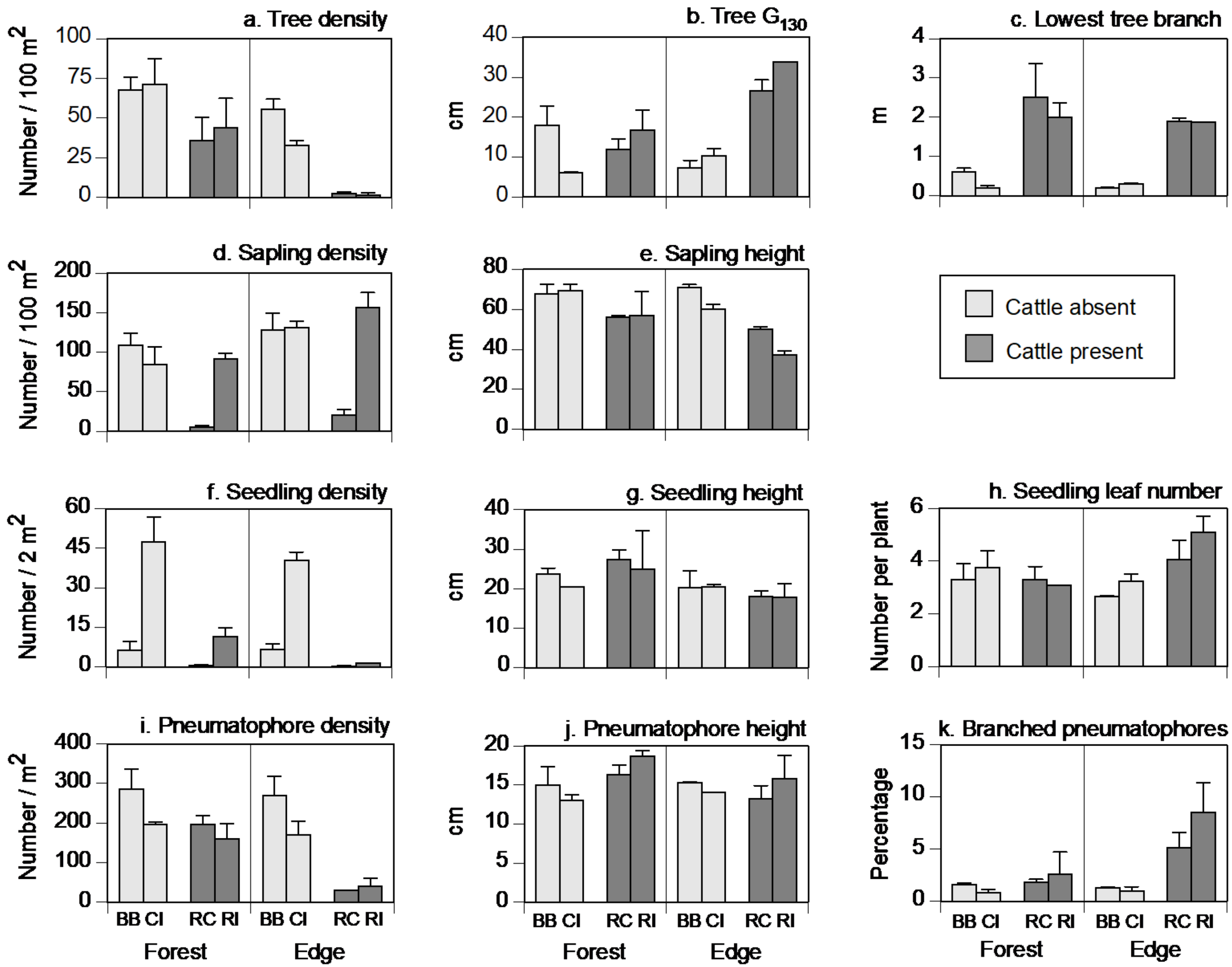
Table 1. Analyses of (a) tree densities, (b) tree girths at 130 cm (G_{130}), (c) tree lowest branch heights (lbh), (d) sapling densities, (e) sapling heights, (f) seedling densities, (g) seedling heights, (h) seedling leaf numbers, (i) pneumatophore densities, (j) pneumatophore heights, and (k) percentage of pneumatophores that were branched for two sites in each of two zones (within the mangrove forest: F, along the landward edge of the mangrove forest: E) at each of two locations in the presence (P: RC=Ryan's Creek, RI=Regatta Island) or absence (A: BB=Berry's Bay, CI=Comerong Island) of cattle. Cattle and Zone are fixed factors and Location is a random factor and nested within cattle. Data were transformed as indicated. Results of Student-Newman-Keuls (SNK) tests for effects of significant interactions. MS=estimate of mean squares. NT=not tested due to significant interactions; NS=not significant, *P < 0.05, **P < 0.01, ***P < 0.001.

		Trees			Saplings		Seedlings			Pneumatophores		
		a. Density	b. G_{130}	c. lbh	d. Density	e. Height	f. Density	g. Height	h. Leaf no.	i. Density	j. Height	k. Branched
Source	d.f. for *F* ratio	MS	MS	MS	MS	MS	MS	MS	MS	MS	MS	MS
Cattle: C	1, L(C)	5148.1*	1.994 NS	12.184**	43.29 NS	1140.2*	13.85 NS	2.33 NS	1.69 NT	61281 NT	10.86 NT	45.08 NT
Location(C): L(C)	2, R	104.3 NS	0.1654 NT	0.115 NS	57.03*	58.6 NS	5.26***	4.32 NS	0.46 NS	9260*	9.06 NS	4.90 NS
Zone: Z	1, L(C) × Z	3969.0*	0.3279 NT	0.226 NS	17.11*	251.0 NS	0.86 NS	99.50*	0.64 NT	26929 NT	5.36 NT	20.89 NT
C × Z	1, L(C) × Z	169.0 NS	0.8581 NS	0.040 NS	0.91 NS	103.6 NS	0.75 NS	40.64 NS	3.80*†	15240*	12.85*	21.36*†
L(C) × Z	2, R	189.3 NS	0.3909*	0.112 NS	0.69 NS	85.5 NS	0.51 NS	3.99 NS	0.40 NS	556 NS	0.14 NS	1.69 NS
Residual: R		237.8	0.070	0.222	1.07	46.8	0.13	33.97	0.51	2077	4.95	3.87
d.f. in Residual		8	7	7	8	8	8	8	8	8	8	8
Transformation		None	ln (*x*+1)	None	sqrt (*x*+1)	None	ln (*x*+1)	None	None	None	None	None
SNK			BB: F > E CI: F = E RC: F < E RI: F < E						F: A = P E: A < P A: F = E P: F < E	F: A = P E: A > P A: F = E P: F > E	F: A < P E: A = P A: F = E P: F > E	F: A = P E: A < P A: F = E P: F < E

†To increase the power of the test for the main effect of interest, C × Z, the estimate of means squares used in the denominator of the *F*-ratio is a pooled estimate from the mean squares of the L(C) × Z interaction and the residual, and then the effect of C × Z were tested with 1 and 10 d.f. (see Winer et al. 1991 for pooling procedures).

Figure Legends

Fig 1. Mean (±se) (a) tree densities, (b) tree girths at 130 cm (G_{130}), (c) tree lowest branch heights (lbh), (d) sapling densities, (e) sapling heights, (f) seedling densities, (g) seedling heights, (h) seedling leaf numbers, (i) pneumatophore densities, (j) pneumatophore heights, and (k) percentage of branched pneumatophores for two sites in each of two zones (within the mangrove forest: Forest, along the landward edge of the mangrove forest: Edge) at each of two locations in the presence (RC=Ryan’s Creek, RI=Regatta Island) or absence (BB=Berry’s Bay, CI=Comerong Island) of cattle.


a. Tree density
Number / 100 m2
b. Tree G130
cm
c. Lowest tree branch
m
d. Sapling density
Number / 100 m2
e. Sapling height
cm
Cattle absent
Cattle present
f. Seedling density
Number / 2 m2
g. Seedling height
cm
h. Seedling leaf number
Number per plant
i. Pneumatophore density
Number / m2
j. Pneumatophore height
cm
k. Branched pneumatophores
Percentage
BB CI RC RI BB CI RC RI
Forest
Edge