RESEARCH REPORT

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Impact of fire and the recovery of molluscs in south-east Australian salt marsh

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This research arose opportunistically after a fire event in an ecologically endangered salt marsh community. This led us to pose the question of whether fire would negatively impact the ecology of molluscs living within the sediment and among both native and invasive salt marsh vegetation and whether fire can act as a large scale and swift method for the control of Spiny Rush. Research was supported by the School of Science and Health at Western Sydney University.

Summary Fire has long been recognised as a natural force in structuring Northern Hemisphere salt marshes, yet little is known about the impact of fire on molluscs and native vegetation dynamics of Southern Hemisphere coastal salt marshes. Following a fire at Ash Island, Hunter River New South Wales, Australia in the summer 2012, we assessed patterns of recovery through time of gastropod populations and resident salt marsh vegetation including biomass for three keystone native plant species, Native Rush (*Juncus kraussii* Hochst.), a chenopod (*Sarcocornia quinqueflora* Bunge ex Ungen-Sternberg A.J. Scott), Salt Couch (*Sporobolus virginicus,* L. Kunth) and the invasive Spiny Rush (*Juncus acutus).* In temperate east-coast Australian salt marshes, Spiny Rush is displacing native salt marsh vegetation. After twelve months, the biomass of Native Rush recovered to similar pre-burn levels. While fire affected the abundance, richness and composition of the gastropod assemblage differences were also largely driven by spatial variability. Gastropod assemblages associated with two of the higher elevation native species (Native Rush and Salt Couch) were impacted the most by fire. Greater abundance (between 1 and 5 orders of magnitude difference in abundance) and richness of gastropods were found in unburnt compared with burnt Native Rush and Salt Couch vegetation, while more gastropods were found in Spiny Rush in one site. Species prevalent in burnt vegetation included larger species of gastropods *Ophicardelus ornatus* (Ferussac, 1821) and *Phallomedusa solida* (Martens, 1878) with an unexpected spike in number of the smaller gastropod *Tatea huonensis* (Tenison-Woods, 1876) in the spiny rush at one site only. In salt marsh habitats, many gastropods have planktonic larval dispersal stages which are dependent on the tidal height for transport and the structural complexity provided by vegetation at settlement. Since fire appears to negatively affect salt marsh gastropod populations within structurally complex Native Rush and Salt Couch, due consideration of the importance of these refuges for gastropods is recommended when fire or other disturbances occur in ecologically endangered salt marsh in the Southern Hemisphere. Managers need to consider spatial heterogeneity of molluscs and their recovery in the event of fire in Southern Hemisphere salt marshes.

Key words: *fire, gastropods, Native Rush, salt marsh, Spiny Rush.*

Introduction

Fire has long been a natural force affecting wetlands (Ford and Grace 1998 and references therein) and has been used as a management tool in some salt marshes (Schmalzer *et al.* 1991; reviewed by Nyman & Chabreck 1995). Fire serves to clear undesirable vegetation, selectively promote favourable food and habitat for wildlife and reduce the risk of large-scale wildfire (e.g. Nyman & Chabreck 1995; Adam 2002). Fire can potentially lead to significant long-term changes in vertical accretion, organic matter, nutrient cycling and species-level composition, structure and dominance (Nyman & Chabreck 1995; DiTomaso 2006). Mollusc species-level responses to fire in salt marsh are dependent upon the life history, functional traits of the species present, environmental factors and disturbance characteristics. Many organisms in salt marsh have larvae which disperse into the water column with late stage larvae returning to the habitat of the adult. The ability to shift or readily adapt to changing conditions is largely dependent upon their physiological tolerance and behavioural capacity (Ross *et al.* 2009; Ross & Adam 2013). Environmental factors associated with a post-burn disturbance including water depth, salinity, rainfall and the frequency, intensity and season of burn are all known to differentially influence species-level composition and dominance (Pennings & Bertness 2001; Mitchell *et al.* 2006).

Studies that have measured the impacts of fire on mollusc communities in a range of habitats have indicated that frequent use of fire can represent a significant long-term threat to the health and diversity of mollusc communities (Nekola 2002; Severns 2005; Ross *et al.* 2009; Bros *et al.* 2011). For example, in a prairie wetland, fire was found to cause a significant reduction in species richness and changed community composition over a three-year period. Interestingly, in the first year post-fire the abundance of molluscs was significantly lower in burnt habitats, but by the third year they were in far greater numbers in burnt habitats than unburnt. This was attributed to an increase in two small native species that probably lacked dominant competitors and found vacant

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niche's post-fire (Severns 2005). Other studies have reported on a quick recovery of the assemblage that was largely determined by pre-existing and post-fire shelter availability (Kiss & Magnin 2003, 2006).

Virtually no information exists on the impacts of fire or other anthropogenic impacts on molluscs in coastal salt marsh (Ross *et al.* 2009). Fire may be positive for some estuarine organisms. Fire can promote vigorous plant regrowth (McAtee *et al.* 1979; Hackney & de la Cruz 1981) with spikes in macronutrients including total nitrogen content (Radho-Toly *et al.* 2001) that some molluscs have been shown to prefer (Iglesias & Castillejo 1999; Cook *et al.* 2000). Similarly, other studies have suggested that spikes of nutrients from oil contamination may lead to increased abundance of molluscs in southern salt marshes (McGuinness 1990).

Southern Hemisphere salt marshes have a long history of exploitation for urban, agricultural and aquacultural, industrial and recreational pursuits. Coastal salt marshes have experienced a range of threats from anthropogenic disturbance (McGuinness 1990; Pennings & Bertness 2001; Ross *et al.* 2009; Ross & Adam 2013) which creates opportunities for non-indigenous plants to successfully colonise and invade (Ruiz *et al.* 1999). In coastal salt marshes of south-east Australia, the non-indigenous Spiny Rush (*Juncus acutus*) native to the Mediterranean is increasingly colonising the upper border of coastal salt marshes (e.g. Burchett *et al.* 1998; Greenwood & MacFarlane 2006; Ross *et al.* 2009; Harvey *et al.* 2010, 2011), particularly along the terrestrial-marsh ecotone (Robinson 1991; Adam 2002; Pickthall *et al.* 2004) and is displacing the Native Rush (*Juncus kraussii* Hochst.) (Zedler & Kercher 2004; Greenwood & MacFarlane 2006). Spiny Rush is listed as a noxious weed in the state of Victoria, Australia, but not in the state of New South Wales (NSW) (Australian Weeds Committee 2015) where if left unmanaged could threaten the stability of coastal salt marshes which are listed as endangered ecological communities in New South Wales under the Biodiversity Conservation Act 2016 and vulnerable under Commonwealth legislation through the *Environment Protection and Biodiversity Conservation Act 1999*. Once established, Spiny Rush forms dense impenetrable monospecific stands and transforms salt marsh communities (Laegdsgaard *et al.* 2009) both in structure and function (Harvey *et al.* 2010, 2011). Very pointed sharp tips and an abundant seed production make control difficult (Parsons & Cuthbertson 1992).

In the summer (January) of 2012, a fire burnt through 7.7 hectares of an endangered salt marsh community on Ash Island, Shortland, located within the Hunter estuary (32°50′ 23.97″, 151°43′ 07.30″). Following this fire, a fully orthogonal design was used to assess the patterns of recovery through time for gastropod populations and resident vegetation including biomass for three keystone indigenous plant species Native Rush, chenopods and Salt Couch (*Sporobolus virginicus* (L.) Kunth.) and Spiny Rush. One management strategy that has been adopted to control the spread of invasive non-indigenous plants is prescribed burning (e.g. Rice 2005; DiTomaso 2006). The effective use of fire for eliminating a particular species in coastal salt marsh is not well known, but it has been used in an attempt to control the invasive native Common Reed (*Phragmites australis* Cav. Trin. ex Steud.) (Mitsch 2000) and less valuable vegetation such as *Typha* L. spp. and *Scirpus* spp. (Smith and Kadlec 1985; Nyman & Chabreck 1995). This study seeks to determine the impact of fire and recovery on the native flora community and associated molluscs and whether fire can act as a large scale and swift method for the control of Spiny Rush.

Methods

Location and plants studied

This study was conducted in a salt marsh at Ash Island, Shortland, New South Wales (NSW), Australia from August 2012 to June 2014. Ash Island is situated within the Hunter Estuary Wetlands Ramsar Site being located approximately seven kilometres north of the Newcastle central business district, 150 km north of Sydney (Brereton and Taylor-Wood 2010). Ash Island is part of the Hunter Wetlands National Park, which combined covers an area of approximately 929 hectares. The salt marsh within the reserve occupies 339 hectares (Brereton and Taylor-Wood 2010). The plants in the salt marsh are typical for NSW (Adam 1981; Adam *et al.* 1988; Pickthall *et al.* 2004). Grey Mangrove (*Avicennia marina* (Forssk.) Vierh.) and River Mangrove (*Aegiceras corniculatum* L. Blanco) dominate the seaward edge. Lower tidal elevations consist of open salt marsh with fairly homogenous areas of the chenopods (*Sarcocornia quinqueflora* Bunge ex Ungen-Sternberg A.J. Scott, *Suaeda australis* R. Brown Moquin-Tandon) and Salt Couch. Higher elevations are dominated by the tussock-forming non-indigenous Spiny Rush and the Native Rush that also occurs in scattered patches at lower elevations (Adam *et al.* 1988). The landward edge bordering the marsh is primarily dominated by Swamp Oak (*Casuarina glauca* Sieber ex Spreng).

The fire of January 2012 burnt 6.8 of 7.9 hectares of vegetation dominated by the spiny rush along with 7.7 out of 9.2 hectares dominated by native salt marsh vegetation. Observations indicate that the above-ground and below-ground biomass of native salt marsh and Spiny Rush was destroyed, although raised and blackened mounds of Spiny Rush were still present. As a result, a unique opportunity arose to explore the impact and recovery of salt marsh vegetation and associated molluscs subjected to fire.

Sampling design

To determine the impact of fire on salt marsh flora and fauna, two sites containing both burnt and unburnt patches of salt marsh vegetation were selected. The sites had similar hydrology (in terms of shore height and tidal inundation) and were approximately 400 m apart. Within each site, two 4 × 4 m plots were selected containing one dominant plant species (native chenopods, Salt Couch, Native Rush and Spiny Rush) in burnt and unburnt areas (8 plots in total in each site). Each plot was divided into a grid of 50 × 50 cm square replicate subplots. Three subplots were

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randomly selected and destructively sampled for flora and fauna on three occasions (winter, spring 2012 and summer 2013), with the first sampling event occurring approximately seven months post-fire. Gastropod samples across the three periods were pooled prior to main analyses because different sampling times were only used to ensure sampling a large portion of gastropod biodiversity post-fire and within-species analyses indicated no time variability (data not shown) which was not our primary focus.

Two techniques were used to target epifaunal and infaunal gastropods. Epifaunal gastropods were directly collected from above-ground plant material and from the soil surface once all above-ground vegetation was removed. Above-ground plant material was removed using electric shears and bagged for additional gastropod removal within the laboratory and biomass estimates. Infaunal gastropods were collected by scrapping the upper 5 cm of the marsh sediment with a butter knife after above-ground plant removal. Soil samples were refrigerated at 4°C prior to coarse sorting using a 500 μm mesh sieve (Ross *et al.* 2009).

All gastropods were identified under a stereomicroscope and stored in 80% ethanol. Individuals deemed dead (without the presence of a soft body beneath shell) were excluded from analyses. Gastropods were counted and identified to family and species level. Juveniles were identified to family level only. Voucher specimens for the eight species identified during this study are lodged at the Western Sydney University, Hawkesbury NSW. Vegetation samples were dried at 75°C for 5 days for biomass estimates (expressed per gram of dry plant weight). To determine the recovery of salt marsh gastropods and vegetation post-fire, both univariate and multivariate analyses were used (see Appendix S1 for more detail).

Results

Plant biomass recovery post-fire

Post-fire recovery of plant biomass differentially varied between plant species and for most species also varied between sites (Fig. 1). By summer 2013, (one year after the fire event) minimal recovery of plant biomass was evident for all species except the Native Rush whereby the biomass in burnt plots recovered to similar levels of unburnt plots 1-year post-fire (Fig. 1b; interaction of wildfire and season, $P > 0.05$). For all other species, post-fire recovery did not occur or was strongly influenced by site variability. For example, the biomass of spiny rush was significantly greater in unburnt compared with burnt plots across the sampling period but there was no recovery of biomass by summer (Table 1; Fig. 1a, SNK for Spiny Rush, interaction of fire and site, $P < 0.05$, unburnt sites $P > 0.05$). The biomass of chenopod and Salt Couch was significantly greater from unburnt compared with burnt plots across the three sampling periods at site one (interaction of fire, season and site, $P < 0.05$) but these trends were not consistent at site two (Fig. 1c, d). At site two, there was no significant difference between unburnt and burnt biomass, across sampling occasions for both species (interaction of fire, season and site, $P > 0.05$) except in the spring sampling of Salt Couch whereby unburnt plots had a significantly greater biomass than burnt plots (Fig. 1c,d; with $P < 0.05$).

Patterns of gastropod abundance and richness

We sampled a total of 37,465 live gastropods, comprising of four gastropod families from four vegetation communities in burnt and unburnt sites. Three species of basal pulmonates in the family Ellobiidae, *Pleuroloba quoyi* (H and A Adams, 1854), *Ophicardelus ornatus* (Ferussac, 1821) and *Ophicardelus sulcatus* (H and A Adams, 1854) in addition to unidentifiable Ellobiidae (Pfeiffer, 1854) juveniles and one species from the family Phallomedusidae, *Phallomedusa solida* (Martens, 1878). Two species of Caenogastropodas from the family Assimineidae, *Cryptassiminea buccinoides* (Quoy and Gaimard 1834) and Hydrobiidae, huonensis (Tenison Woods 1876). Overall, for most of the native salt marsh species the abundance of gastropod fauna was less in burnt habitats but this is spatially variable. Gastropod richness also varied inconsistently between unburnt and burnt habitats and between sites (Table 2; Fig. 2). For example, there was significantly greater abundance and richness of gastropods in unburnt than burnt Native Rush at site 2 but not at site 1 (Fig. 2b,f) and three was significantly greater gastropod abundance and richness in unburnt chenopod vegetation at site 1 but abundance was only significantly greater in unburnt compared with burnt chenopod vegetation at site 2 (Fig. 2d,h). Contrasting this, the abundance and richness of gastropods collected from burnt habitats of Spiny Rush were more than double those from unburnt habitats at site one but at site 2 gastropods were virtually absent from burnt vegetation (Fig. 2a,e). High spatial heterogeneity in gastropods was evident in chenopod vegetation with overall greater abundance and richness of gastropods collected from site 2 (Fig. 2c,g).

Gastropod assemblages

There were marked differences in the gastropod assemblage collected between unburnt and burnt salt marsh vegetation but differences were also strongly driven by spatial heterogeneity (Table 3, Fig. 3). For example, at each site gastropod assemblages varied significantly between unburnt and burnt vegetation for each vegetation community. Indeed, per cent dissimilarity was in excess of nearly 54% across all species. But marked differences between sites were also apparent in all unburnt vegetation communities with dissimilarities in excess of 70% for all species except for the Native Rush where communities were similar. Differences between sites of burnt vegetation were also evident for all species except for chenopods (Table 3, Fig. 3c). For detailed analysis of similarity indices of assemblage differences, see Appendix S1 (Tables 3 and 4; Fig. 3).

Discussion

Fire impacts the recovery of gastropod assemblages and salt marsh vegetation. Twelve months post-fire only the biomass of Native Rush recovered to similar levels of unburnt vegetation. Gastropod

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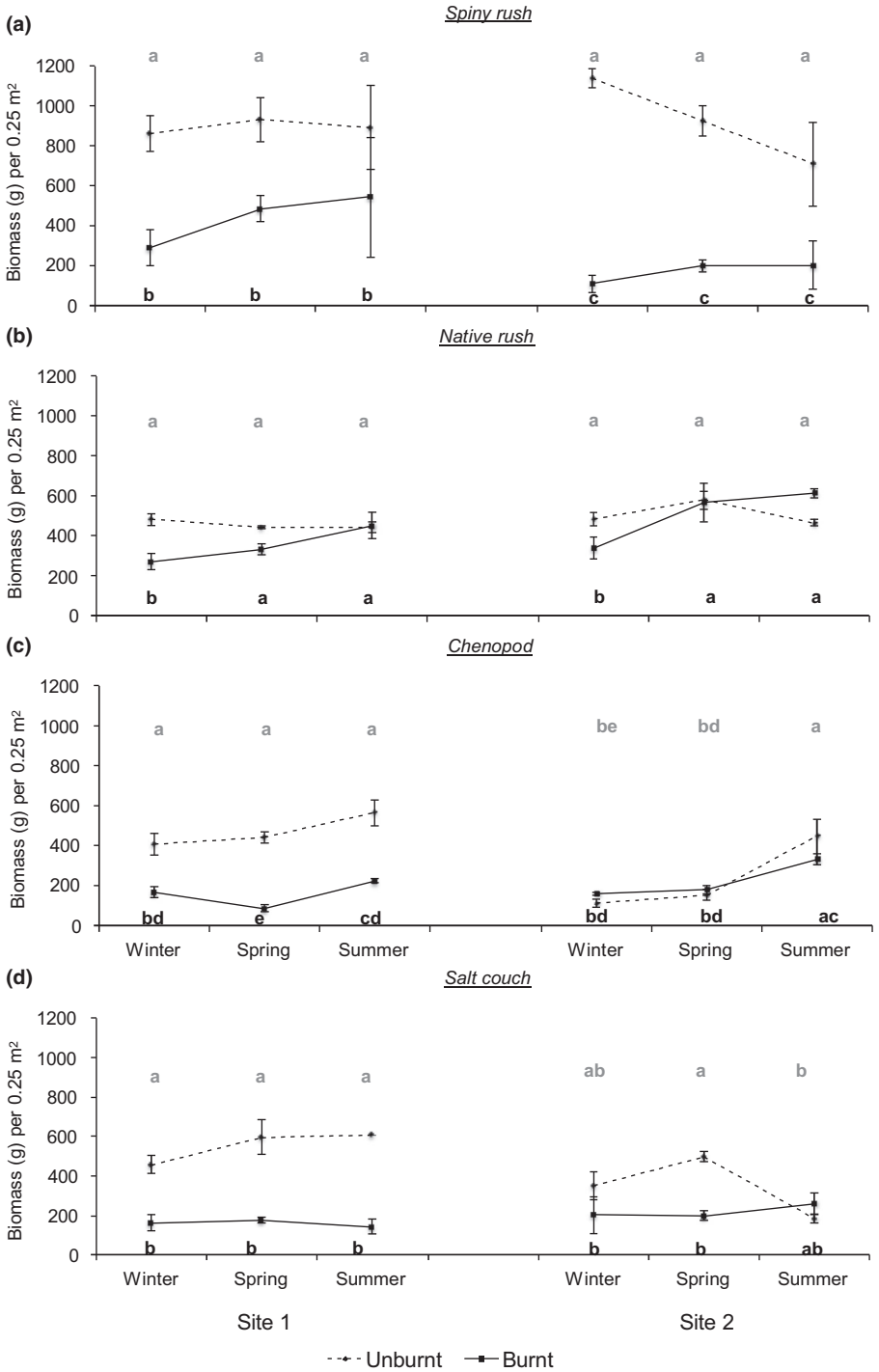


Figure 1. Mean biomass (grams) (±SE, n = 3) collected from unburnt and burnt plots of (a) Spiny rush, (b) Native rush, (c) Chenopod and (d) Salt couch during winter, spring 2012 and summer 2013 at site 1 and site 2, Ash Island. Different letters indicate statistical significance according to Student–Newman–Keuls multiple comparisons test (SNK) at $P < 0.05$ for (a) Spiny rush (fire × site), (b) Native rush (fire × season) (c) Chenopod (fire × season × site) and (d) Salt couch (fire × season × site) with grey letters for unburnt vegetation comparisons and black for burnt.

assemblages associated with two of the higher elevation native species (Native Rush and Salt Couch) were impacted the most by fire. Greater abundance and richness of gastropods was found in unburnt compared with burnt Native Rush and Salt Couch vegetation. While fire affected the abundance, richness and composition of the gastropod assemblage differences were also largely driven by spatial heterogeneity within the salt marsh. Differences in gastropod species-level composition varied strongly with high dissimilarity between unburnt and burnt vegetation for all species but the strength

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Table 1. Results of three-factor, analysis of variance (ANOVA) for the effect of fire (unburnt or burnt vegetation), season (winter, spring or summer), location (Site 1 or Site 2) and their interactions on the biomass (grams) of dried plant material collected on the spiny rush and native rush, chenopod and salt couch at Ash Island

Source	df for *F*	Spiny rush		Native rush		Chenopod		Salt couch	
		F	*P*	*F*	*P*	*F*	*P*	*F*	*P*
Fire (F)	1, F × S	44.92	**<0.01**	1.93	0.39	0.74	0.55	4.31	0.29
Season (Se)	2, Se × S	0.96	0.40	3.64	0.22	4.84	0.17	4.85	0.17
Site (S)	1, R	6.11	**0.02**	13.91	**<0.01**	11.30	**<0.01**	1.35	0.26
F × Se	2, F × Se × Si	1.57	0.23	792.46	**<0.01**	0.71	0.59	0.28	0.78
F × S	1, R	6.27	**0.02**	4.10	0.06	65.96	**<0.01**	11.67	**<0.01**
Se × S	2, R	0.16	0.85	1.76	0.19	7.87	**<0.01**	0.40	0.68
F × Se × Si	2, R	0.19	0.83	0.01	0.99	4.87	**<0.01**	4.30	**0.03**
Residual: *R*	24								

Biomass per 0.25 m^2 was transformed to ln (x + 1). Statistically significant effects are highlighted with bold.

Table 2. Results of two-factor, analysis of variance for the effect of fire (unburnt or burnt vegetation; df = 1,1), location (Site 1 or Site 2; df = 1,32) and their interaction (df = 1,32) on the total abundance and richness of gastropods collected on the spiny rush and native rush, chenopod and salt couch at Ash Island. Data for all variables were transformed to ln (x + 1).

Variable	Fire		Site		Fire × Site	
	F	*P*	*F*	*P*	*F*	*P*
Spiny rush						
Abundance	0.26	0.70	112.50	**<0.01**	41.00	**<0.01**
Richness	0.04	0.87	71.00	**<0.01**	62.15	**<0.01**
Native rush						
Abundance	2.11	0.38	21.03	**<0.01**	22.56	**<0.01**
Richness	0.66	0.57	60.80	**<0.01**	48.70	**<0.01**
Chenopod						
Abundance	17.23	0.15	19.25	**<0.01**	0.58	0.45
Richness	11.06	0.19	6.23	**0.02**	0.52	0.52
Salt couch						
Abundance	2.13	0.38	0.41	0.53	42.45	**<0.01**
Richness	3.86	0.30	17.96	**<0.01**	10.51	**<0.01**

Statistically significant effects are highlighted with bold. The values '*F*' and '*P*' refer to the Fisher statistic and *P*-value, respectively.

of differences was also determined by site variability. Fire can reduce the short-term recovery for gastropod species associated with native coastal salt marsh and may reduce the recovery and spread of the Spiny Rush.

We observed differences in the post-fire vegetation response between species and sites. This is unsurprising as ecologists have long recognised species-specific responses (Lyon & Stickney 1976; Turner *et al.* 1994; Whelan 1995; Lentile *et al.* 2007; Vierling & Lentile 2008). Responses may be explained by the complex interactions between terrain, weather, pre-fire vegetation composition, and the life history strategies and adaptations of individual plant species (Lentile *et al.* 2007). Indeed past studies indicate that recovery rates of vegetation cover and or biomass are species specific with some communities returning to pre-burn levels in under a year. For example, Native Rush has been found to generally recover quickly in as little as 6 months while *Spartina* can take several years (Isacch *et al.* 2004; reviewed by Mitchell *et al.* 2006). In this study, only Native Rush reached similar biomass estimates to unburnt sites 12 months post-fire. Regardless of a speedy recovery, the gastropod abundance, richness and assemblage were still considerably different to pre-fire levels. Managers working in this dynamic system need to consider individual species differences and monitor disturbance impacts at fine spatial and temporal scales when assessing recovery.

For both of the higher elevation native species (Native Rush and chenopods), there was generally greater abundance and richness of gastropods at unburnt compared with burnt sites. These results are comparable to those obtained in other habitats (Nekola 2002; Kiss and Magin p2003; Severns 2005; Bros *et al.* 2011) but differences in this study were not always consistent between sites, dependent on spatial variability of gastropods. For the lower elevation species where abundances of gastropod in chenopod vegetation was an order of magnitude less, the abundance and richness of gastropods varied depending on site rather than whether they were burnt or unburnt. Unexpectedly, more than double the abundance and richness of gastropods were found associated with burnt than unburnt Spiny Rush vegetation at site 1 (comprised mainly of *T. huonensis*). In contrast, gastropods were virtually absent from burnt Spiny Rush at site 2. Gastropods can recolonise salt marsh vegetation using two mechanisms: migration of adults from surrounding unburnt to burnt habitats or planktonic larval recruitment (Roach 1998; Roach & Lim 2000; Ross 2001). The presence of Ellobiidae juveniles more often in unburnt native rush and chenopod vegetation indicates that late stage larvae returned to the habitat of the adult on incoming spring tides (Ross 2001, 2006; Mazumder *et al.* 2006).

The variation in gastropod recovery post-fire between sites could have been due to variation in microhabitats provided

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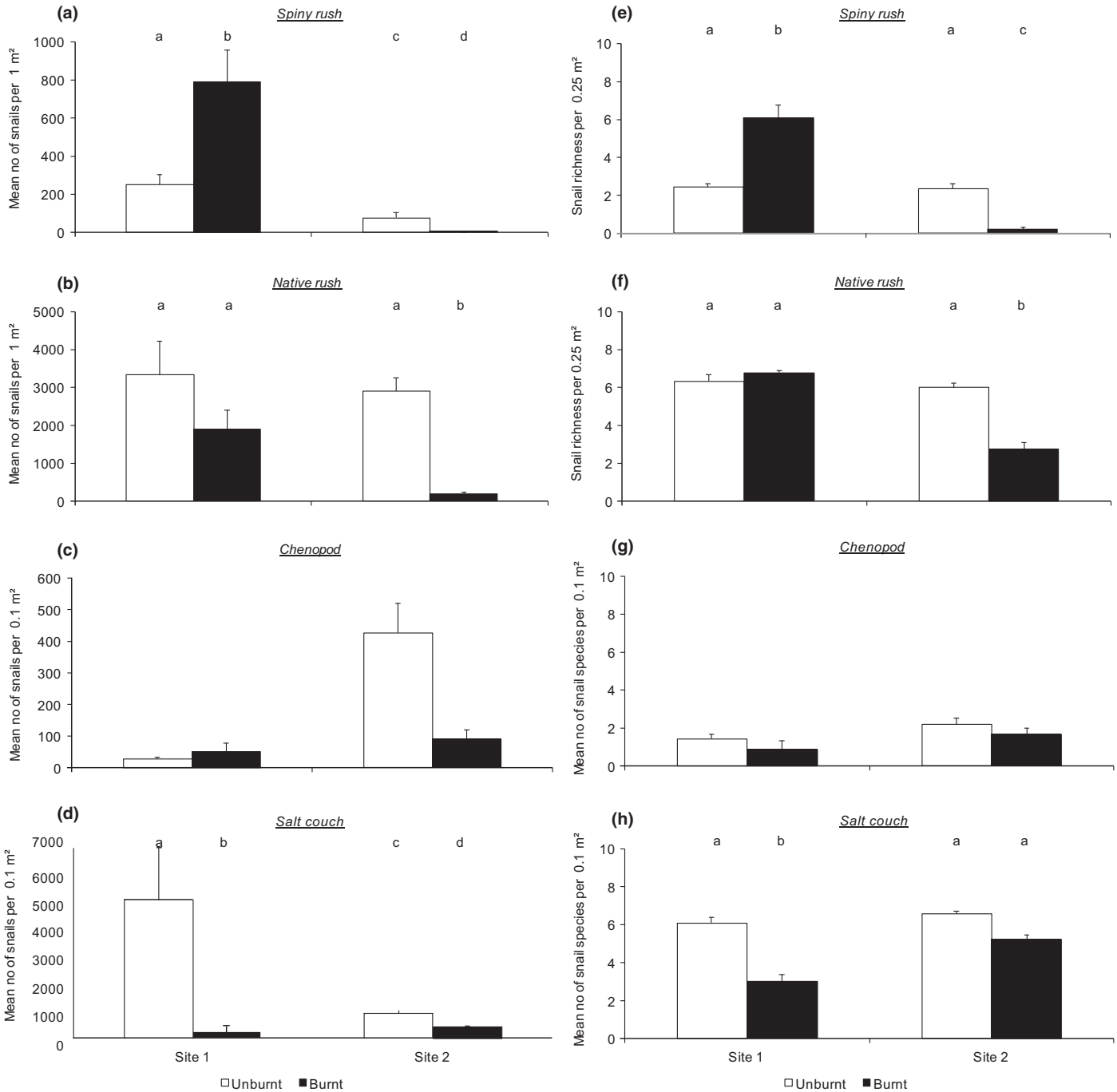


Figure 2. Mean number (±SE) of gastropod individuals (a–d) and species (e–h) found in unburnt and burnt plots of salt marsh vegetation across sites. Bars with different letters are significantly different at $P < 0.05$ according to Student–Newman–Keuls pairwise comparison tests.

by the salt marsh vegetation including small scale patterns of hydrology. Community composition post-fire has been shown to be dependent on existing shelters and habitat provided (Kiss & Magnin 2003, 2006). Nekola (2002) and Severns (2005) demonstrated the critical importance of thatch layering for the colonisation of molluscs post-fire. Gastropods in salt marshes are often found between the stems and leaves of native tussock and grasses and large variation in abundance at small spatial scales is a feature of these habitats (Ross *et al.* 2009). In this study, high numbers of gastropods, especially *Ophicardelus ornatus* and *O. sulcatus,* were found living between the stems of both Native Rush and Salt Couch (Richardson *et al.* 1998; Green *et al.* 2009; Ross *et al.* 2009). The stems and leaves of these species interlink to form a thick roof-like cover that provides protection and shelter for gastropods. Depending on intensity, fire can essentially destroy the shelter these habitats provide.

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Table 3. Results of two-factor, PERMANOVA for the effect of fire (unburnt or burnt vegetation), location (Site 1 or Site 2) and their interaction on the gastropod assemblage collected from the spiny rush, native rush, chenopod and salt couch at Ash Island. Results of *a posteriori* pairwise tests in PERMANOVA and per cent dissimilarity for the significant interaction between fire and site

Gastropod assemblages	df	Pseudo-*F*	*P* (perm)	Pairwise (Fire × Site)	*t*	*P* (perm)	Dissimilarity (%)
Spiny rush				Unburnt vs. Burnt			
Fire	1	2.11	0.50	Site 1	2.38	**<0.01**	73.25
Site	1	8.78	**<0.01**	Site 2	1.98	**0.02**	85.79
Fire x Site	1	2.92	**0.01**	Site 1 vs. Site 2			
Residuals	25			Unburnt	2.07	**<0.01**	73.11
Total	28			Burnt	2.76	**0.02**	98.16
Native rush				Unburnt vs. Burnt			
Fire	1	2.77	0.25	Site 1	2.86	**<0.01**	63.89
Site	1	9.50	**<0.01**	Site 2	5.22	**<0.01**	95.06
Fire x Site	1	9.23	**<0.01**	Site 1 vs. Site 2			
Residuals	32			Unburnt	0.87	0.46	34.78
Total	35			Burnt	3.67	**<0.01**	86.72
Chenopod				Unburnt vs. Burnt			
Fire	1	0.23	0.83	Site 1	1.87	**0.04**	68.74
Site	1	4.74	**<0.01**	Site 2	2.69	**<0.01**	62.86
Fire x Site	1	8.07	**<0.01**	Site 1 vs. Site 2			
Residuals	26			Unburnt	4.26	**<0.01**	85.91
Total	29			Burnt	0.82	0.55	53.39
Salt couch				Unburnt vs. Burnt			
Fire	1	2.29	0.25	Site 1	4.06	**<0.01**	96.09
Site	1	22.14	**<0.01**	Site 2	4.46	**<0.01**	53.99
Fire x Site	1	10.48	**<0.01**	Site 1 vs. Site 2			
Residuals	32			Unburnt	4.55	**<0.01**	81.29
Total	35			Burnt	**3.48**	**<0.01**	66.76

Statistically significant effects are highlighted with bold.

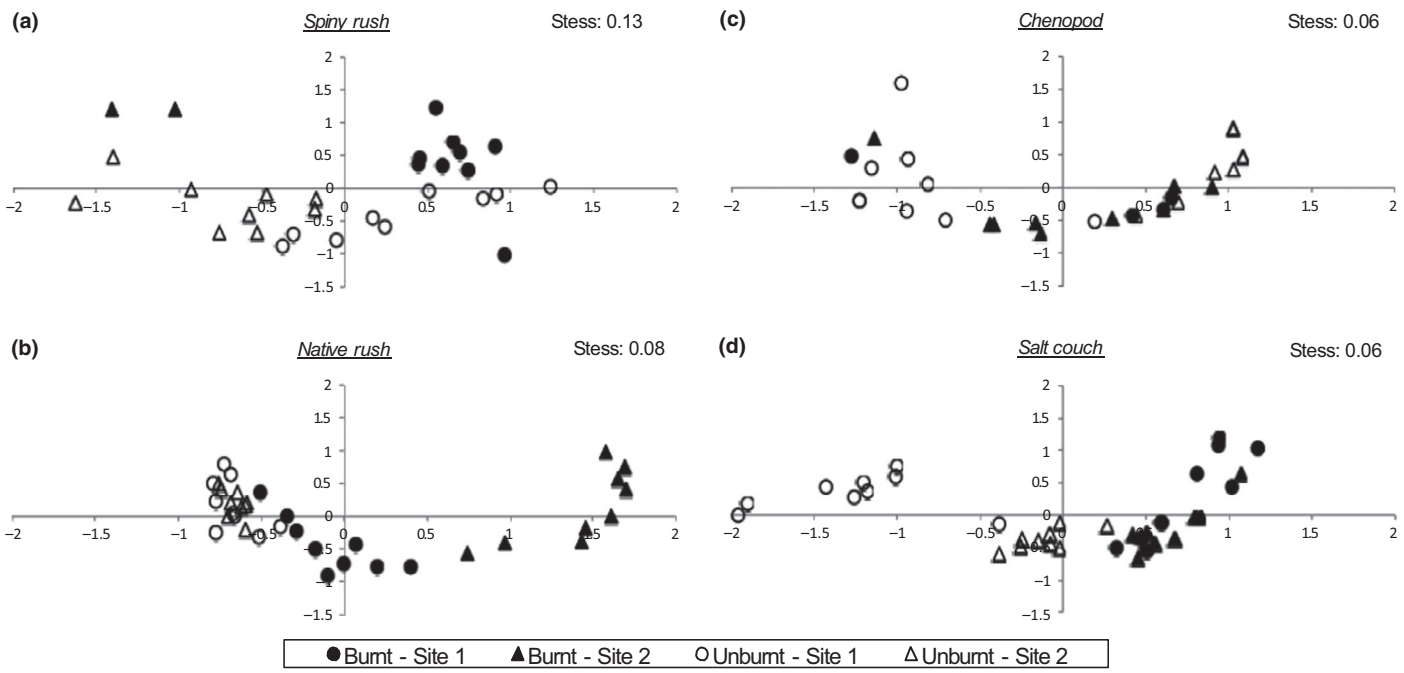


Figure 3. Non-metric, multidimensional scaling plot of gastropod assemblages from replicate samples (one point per quadrat) collected from the invasive rush (a) Spiny rush, (b) Native rush, (c) Chenopod and (d) Salt couch in unburnt and burnt quadrats across two sites on Ash Island.

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Table 4. Results of two-factor, SIMPER for the effect of fire (unburnt or burnt vegetation) on the gastropod assemblage collected from the spiny rush and native rush, chenopod and salt couch at Ash Island. The average Bray–Curtis dissimilarities between all pairs are given for each species collected in unburnt and burnt sites. For each species, the average abundance is recorded, along with the % contribution cumulative contribution to overall group similarity with species ordered in decreasing contribution to overall group similarity

	Unburnt Average abundance	Burnt	Contrib.%	Cum.%		Unburnt Average abundance	Burnt	Contrib.%	Cum.%
Site 1					Site 2				
Spiny rush			Average dissimilarity = 73.25					Average dissimilarity = 85.79	
O. ornatus	178.22	242.22	30.63	30.63	*C. buccinoides*	59.11	0	69.75	69.75
P. solida	1.78	173.78	22.74	53.37	*P. solida*	12	8	22.01	91.76
T. huonesis	0.44	222.67	22.1	75.47	*O. ornatus*	7.56	0	7.09	98.85
C. buccinoides	68.44	35.11	11.82	87.29	*P. quoyi*	0.89	0	1.15	100
Ellobiidae juv.	0	35.56	5.13	92.42	*O. sulcatus*	0	0	0	100
O. sulcatus	1.78	60	5	97.42	Ellobiidae juv.	0	0	0	100
P. quoyi	0.44	20.89	2.58	100	*T. huonesis*	0	0	0	100
Native rush			Average dissimilarity = 63.89					Average dissimilarity = 95.05	
T. huonesis	2898.22	866.67	68.25	68.25	*T. huonesis*	2559.11	0	86.17	86.17
O. ornatus	32	470.22	15.37	83.62	*P. solida*	156	52.89	4.48	90.64
P. solida	148.44	255.56	5.86	89.48	*C. buccinoides*	34.67	104.44	2.97	93.62
Ellobiidae juv.	45.78	129.78	3.71	93.19	*O. sulcatus*	68.89	0	2.19	95.81
O. sulcatus	82.67	112.89	3.26	96.45	Ellobiidae juv.	47.11	1.78	1.79	97.6
P. quoyi	104.44	23.11	2.1	98.55	*O. ornatus*	2.67	36.89	1.29	98.9
C. buccinoides	11.56	54.67	1.45	100	*P. quoyi*	35.11	0.44	1.1	100
Chenopod			Average dissimilarity = 68.74					Average dissimilarity = 62.86	
P. solida	23.56	114	89.42	89.42	*P. solida*	416	95	95.21	95.21
C. buccinoides	4.89	2	8.8	98.21	*C. buccinoides*	0.89	4	1.66	96.86
P. quoyi	0.44	1	1.12	99.34	*O. ornatus*	6.22	2	1.51	98.37
O. sulcatus	0	1	0.66	100	*P. quoyi*	2.22	1.5	1.2	99.58
O. ornatus	0	0	0	100	*O. sulcatus*	1.33	0	0.42	100
Ellobiidae juv.	0	0	0	100	Ellobiidae juv.	0	0	0	100
T. huonesis	0	0	0	100	*T. huonesis*	0	0	0	100
Salt couch			Average dissimilarity = 96.09					Average dissimilarity = 53.99	
T. huonesis	4480.44	0	81.23	81.23	*O. sulcatus*	324.89	17.33	39.08	39.08
O. sulcatus	188	0.89	7.01	88.24	*P. solida*	250.67	352.89	22.03	61.11
P. solida	61.33	101.33	3.29	91.52	*P. quoyi*	149.78	14.67	17.44	78.56
P. quoyi	92.44	1.78	3.21	94.73	*C. buccinoides*	97.33	46.67	9.2	87.75
C. buccinoides	93.33	11.11	2.68	97.41	*O. ornatus*	54.67	11.11	6.02	93.78
Ellobiidae juv.	162.22	0	2.2	99.61	Ellobiidae juv.	45.33	1.78	5.42	99.2
O. ornatus	6.22	12	0.39	100	*T. huonesis*	5.78	1.33	0.8	100

Some of the spatial differences in abundance and richness of gastropods may have been due to differential supply or settlement of gastropod larvae between sites, which has been found in studies which have investigated anthropogenic impacts on gastropods (Ross 2006). Alterations in vegetation structure can change the flow rate of water across the estuarine marsh surface and affect larval supply and settlement (Irlandi & Crawford 1997; Ross 2001; Whitman & Reidenbach 2012). This is likely to be more significant for higher elevation species which are flooded less frequently than the dense near shore low growing succulent beds of chenopods that were predominately influenced by spatial components in this study. The dense root mounds of Spiny Rush were observed to be at the highest elevations compared with the surrounding salt marsh. As elevation increases, the more limited the likelihood for larval supply, settlement and subsequent colonisation of gastropods. The effects of fire may have benefited some larger species of gastropod. Species with larger shells can generally retain water for longer and, hence, are less prone to desiccation (Lowell 1984). In this study, the biomass of Spiny Rush was not as destructively burnt at site one compared with site two. Because patches of vegetation were still present at site one, larger gastropods including *O. ornatus, Phallomedusa solida* and the smaller *Tatea huonensis* were found in burnt spiny rush vegetation may have had the opportunity to explore food availability and habitat in newly vacant niches. The spike in number by the smaller gastropod *Tatea huonensis* (Tenison-Woods, 1876) in Spiny Rush at one site only, although unexpected, is not an uncommon pattern for this species (Ross *et al.* 2009). Indeed these species were generally present in all of the burnt salt marsh vegetation communities representing indicator species for burnt habitat. In contrast, juveniles from the family Ellobiidae were in low densities or and generally absent from burnt vegetation indicating a low tolerance of burnt conditions.

Variability of gastropods in south-eastern salt marshes among sites is common (Ross *et al.* 2009). Without pre-burn data, this study should be considered as a snapshot, and due attention should be given to

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the spatial and temporal variation throughout the salt marsh with particular emphasis on fire severity. For example, because this study was representative of only one location, there is a constraint to understanding gastropod responses and the heterogeneity of marshes more generally in NSW. Nevertheless, fire differentially impacted the salt marsh plant community and gastropods in the first year post-fire. Management of anthropogenic disturbances in southern salt marshes need to consider the significant abundances of gastropods in the habitat provided by the vegetation Native Rush and Sal Couch. While the trophic cascades responsible for salt marsh regulation in Northern Hemisphere are not known as significant processes for Southern Hemisphere salt marshes, the role of the significant numbers of gastropods in Southern Hemispheres remains unknown (Altieri *et al.* 2012). If burning were to be used as a management strategy to control the spread of spiny rush in east-coast Australian salt marshes, caution must be taken to eliminate or at least significantly reduce the impact of fire on native vegetation, particularly native rush and salt couch which are commonly found interspersed with this species. Further studies are needed to assess the impact and type of prescribed burn required to control the Spiny Rush, optimal timing of fire and intervals between in addition to use with other integrated management techniques. A site by site management framework would need to be applied to conserve the vegetation and resident gastropod fauna in the context of disturbance. Broad-brush strategies applied to different salt marsh vegetation are unlikely to be suitable. This study underlines the need for managers to be aware of the broad and fine spatial and temporal scale when assessing post-disturbance impacts and recovery; perhaps this is even a unique feature of salt marsh, fine scale unpredictability. Many managers are naive to that fact, yet the data presented here showcase stochasticity. With regard to legal responsibilities regarding burning in salt marsh, prescribed public authorities wishing to undertake prescribed burning or mechanical disturbance within the Endangered Ecological Community, *Coastal salt marsh in the NSW North Coast, Sydney Basin and South East Corner bioregions*, application of the Bushfire Assessment Code applies. The Code indicates fire or mechanical disturbance is not permitted in Coastal salt marsh. If however, burning is proposed for the management of Spiny Rush within Coastal salt marsh in NSW, the Bushfire Assessment Code does not apply, and further assessment under the Federal *Environmental Planning and Assessment Act 1979* is required to evaluate the environmental risks and consequences of prescribed burning. Since fire appears to negatively affect native salt marsh gastropod populations over very short distances within structurally complex native rush and salt couch, due consideration of these refuges for gastropods is recommended when fire or other disturbances occur in ecologically endangered salt marsh in the Southern Hemisphere. Overall, this study is useful for managers of endangered ecological habitats who need to be aware that fire can occur in Southern Hemisphere salt marshes and have contingency plans in the event of occurrence.

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Supporting Information

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Appendix S1. Statistical analyses

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