



Mangrove distribution and mosquito control: transport of *Avicennia marina* propagules by mosquito-control runnels in southeast Queensland saltmarshes

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Abstract

The saltmarsh–mangrove interface generally constitutes the landward boundary for the grey mangrove *Avicennia marina* var. *australasica*, the most widespread species on southeast Queensland shores. *A. marina* produces buoyant propagules, which are dispersed by tidal waters, only infrequently transported to saltmarsh by the highest spring tides. We predicted that runnelling, a form of habitat modification for mosquito control, transports and deposits mangrove propagules to saltmarsh because the runnels carry low-amplitude tides that would not normally inundate higher regions of the marsh. To test this, groups of marked *A. marina* propagules were released at three runnelled saltmarshes in southeast Queensland during high-amplitude, flooding and low-amplitude, non-flooding tidal events. The distance propagules were transported from their original starting positions on the saltmarsh–mangrove interface was measured and analysed to detect differences among groups at different distances from runnels. Groups of propagules released within 10 m of a runnel were always transported significantly further from the starting position and further up the saltmarsh shore after both flooding and non-flooding tides than any other groups. In addition, the pattern of stranding on saltmarsh for significantly different groups was closely associated with the path of runnel construction so that propagules were located either in the runnel or in depressions linked to the runnel that had been isolated mosquito-breeding pools prior to runnelling. Observations of *A. marina* plants at other runnelled sites suggest that propagules transported by runnels can establish and develop to maturity, at least in depressions and runnels, in saltmarsh. The fact that runnels transport propagules to regions of the saltmarsh beyond their normal limits of dispersion suggests a possible advantage for landward extension of the intertidal distribution of *A. marina* at runnelled sites and should be considered in saltmarsh management and mosquito control programmes in southeast Queensland.

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1. Introduction

Coastal mangrove and saltmarsh communities experience similar hydro-edaphic conditions (Patterson, McKee, & Mendelsohn, 1997), but are distributed across different intertidal and latitudinal gradients (Adam, 1994). When representative species from both communities overlap in range, physical adaptations to environmental stresses (such as tidal periodicity and

amplitude) often restrict their distribution to specific intertidal limits (Adam, 1994; Mazda, Kanazawa, & Kurokawa, 1999; Naidoo, Rogalla, & von Willert, 1997; Saenger, Specht, & Chapman, 1977).

The grey mangrove, *Avicennia marina* var. *australasica* (Walp.), is the only variety found in eastern Australia (Clarke, 1993) and is common on the Queensland coast. The intertidal distribution of mature *A. marina* is between mean high water and mean sea level (Clarke & Myerscough, 1993) and the low density of *A. marina* on saltmarsh is due mainly to limited seed dispersal beyond the mangrove zone (Clarke & Hannon, 1969, 1970, 1971). *A. marina* seeds are produced within

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large cryptoviviparous fruit (Clarke, 1993; Hutchings & Saenger, 1987), the embryo encased in a protective pericarp. Transport of *A. marina* propagules is determined, in part, by buoyancy properties of the pericarp and the embryo. Fruit with pericarp intact can float in seawater for up to 24 h before the pericarp is shed, at which time fruit sink for periods of at least 48 h before refloating (Clarke & Myerscough, 1991).

A. marina propagules are usually transported by seawater, and their capacity for dispersal from the parent plant is dependent on tidal frequency and amplitude (Clarke & Myerscough, 1993). Propagules often strand and establish close to the parent plant population (Clarke, 1993), but are infrequently transported by the highest spring tides beyond the mangrove zone to saltmarsh on the landward side or mud flats on the seaward side (Clarke & Hannon, 1969). In addition, some land use practices in saltmarsh may create favourable conditions for the landward colonization of *A. marina* into saltmarsh by altering chemical (Anwahi, Zarouni, Janahi, & Cherian, 1998; McTainsh, Iles, & Saffigna, 1986) or physical (Dale, Hulsman, Easton, & Kay, 1989; Saintilan & Williams, 1999) conditions that facilitate mangrove seedling establishment.

Runnels are a form of mosquito control, which function to provide tidal access to isolated mosquito-breeding pools located high on the marsh via small channels that link the tidal source to graded shore regions of the saltmarsh (Dale & Hulsman, 1990). Runnels are shallow (<30 cm depth), spoon-shaped channels constructed to a maximum gradient of 1 : 1000 (see Hulsman, Dale, & Kay, 1989 for a full description). The physical position of a runnel on the shore is determined by the location of mosquito-breeding pools as well as elevation and topographic features of the saltmarsh (Dale, Hapgood, Kay, Morris, & Standfast, 1998). The area of saltmarsh immediately surrounding a runnel (approximately 2500 m²) is slightly lower in elevation than other regions of the saltmarsh and can function as a natural drainage line. Together with the depth of the runnel, these features enable slow water movement through runnels during low-amplitude tides that would not normally flood higher regions of the marsh. The net result for mosquito control is increased frequency of tidal inundation of isolated breeding pools and changes in water quality that adversely affect larval maturation and survival via increased access to predators, tidal flushing and reduced oviposition sites (Dale & Hulsman, 1990; Hulsman et al., 1989). Following runnel construction, isolated pools remain on the marsh as slight depressions, which are inundated by runnel-transported tides and do not support mosquito-breeding.

In this study, the role of mosquito-control runnels in transporting and depositing mangrove propagules onto saltmarsh is explored. Propagules of *A. marina* are

usually transported and deposited within similar intertidal limits as the parent plants and are rarely carried to saltmarsh (Clarke & Myerscough, 1991). This might be explained by limited dispersal mechanisms for propagules to reach favourable areas of saltmarsh above their usual intertidal limit. If runnelling increases the frequency of tidal inundation of saltmarsh, it may also provide an alternate dispersal method for buoyant propagules to be deposited onto saltmarsh. The colonization of saltmarsh areas by mangroves may result from two factors. Mosquito-control may affect deposition of mangrove propagules, allowing propagules to travel to places on the marsh they would not otherwise get to, and/or it may affect survivorship and establishment rates once propagules are on the marsh by altering hydrological regimes. This study specifically examines the former. The main hypotheses, which will test this model, are:

1. that propagules will be transported further onto saltmarsh in runnels than in adjacent unrunnelled saltmarsh;
2. that propagules are more likely to be transported by runnels if their point of origin is close to the runnel.

2. Materials and methods

2.1. Study area

Propagule-release experiments were conducted at three saltmarshes (hereafter called 'sites') in southern Moreton Bay, southeast Queensland, Australia (Fig. 1) between August and November 2000. Criteria for the selection of sites in the experiment included the presence of mosquito control runnels (Hulsman et al., 1989), fruiting *A. marina* and a clearly defined intertidal boundary (Clarke & Myerscough, 1993) between *A. marina* and

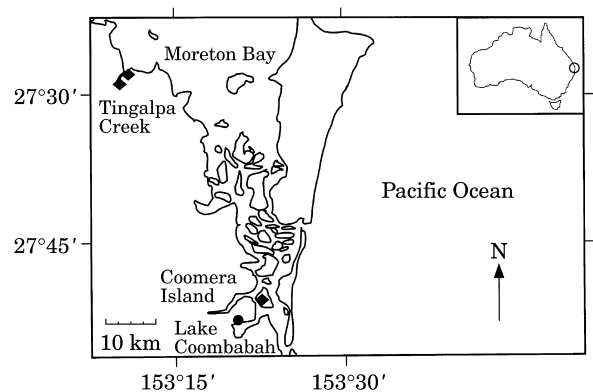


Fig. 1. Location of saltmarsh sites (shown as black diamonds) in southern Moreton Bay where propagules were released. Lake Coombabah (black circle) was the collection site for propagules.

saltmarsh (hereafter called the ‘saltmarsh–mangrove interface’). The three sites experienced a tidal range of approximately 2 m and had a relief of about 0.5 m.

The extent of saltmarsh on the shore was bounded by mangroves at the mean high water neap tide level (low on the shore) and extended into mixed scrubland or forest beyond mean high water spring tide levels. From the shore and beyond the mangrove border, low chenopod shrublands of *Sarcocornia quinqueflora* and *Suaeda australis* were formed on soils flooded by spring tides. Closed grasslands and salt meadows dominated by *Sporobolus virginicus* occurred towards the landward side of the low shrublands and were on substrate only flooded by the highest spring tides. The patterns of tidal submergence and exposure at the three saltmarsh sites are important features of the biology of endemic species and similar processes are responsible for the formation of saltmarsh in both the southern and northern hemispheres (Adam, 1990). However, because the elevation of most Australian saltmarsh precludes them from daily tidal submergence the stress on biota from salinity and moisture fluctuations is much greater than for the *Spartina*-dominated marshes of North America (Adam, 1995).

Propagules of *A. marina* were collected from a single mangrove population at the northern shore of Lake Coombabah (Fig. 1). Fruits were collected from randomly chosen *A. marina* by shaking trees and gathering fallen propagules or by selecting material that appeared to be fresh amongst already fallen debris. All collected fruits were sorted and those with split or damaged pericarps were discarded.

2.2. Pericarp loss experiment

Branding the pericarp to identify propagules for mark and recovery experiments can interfere with pericarp retention (Clarke, 1993), and this could affect manipulative experiments investigating transport of *A. marina* propagules. Clarke (1993) also reported reduced buoyancy and interference with retention of the pericarp following physical labelling with fish tags, incisions and pen marks. Given Clarke’s (1993) observations, it was important, in this experiment, to establish the probability of marked propagules retaining their pericarps for at least one tidal phase following release, since pericarp retention/loss affects buoyancy (Clarke, 1993). Twenty propagules were randomly selected from those collected at Lake Coombabah to test the effects of marking with a permanent pen on propagule buoyancy.

Ten propagules were given a numerical mark on each side of the pericarp using waterproof permanent felt pens, and 10 propagules remained unmarked. All propagules were floated in an artificial seawater solution and monitored for a total of 12 h to record pericarp loss. Observations were made hourly for the first 6 h and then

every second hour. A period of 12 h was similar to the time that marked propagules would remain under the influence of one tidal phase in the field.

The proportion of propagules having lost their pericarp was not significantly different in the control and marked treatments ($\chi^2 = 0.208$; $df = 1$; $P > 0.05$). Propagules could therefore be marked with permanent felt pens in the release experiment without concern for effects on pericarp retention and buoyancy over one tidal event.

2.3. Propagule transport experiment

The location of runnels on the saltmarsh determined the positioning and size of the experimental sites. The experimental site, including the runnel, was homogeneous in terms of vegetation, elevation and topographic features. In addition, prior knowledge of the pattern of tidal inundation aided the selection of ‘starting’ positions for groups of propagules, which would receive tidal waters at the same time.

At each site, five groups of 15 marked propagules were placed at 10 m intervals along the tidal inlet and within 1 m of the saltmarsh side of the saltmarsh–mangrove interface (Fig. 2). However, at Tingalpa Site 2, four groups of 14 and one group of 13 propagules were released.

The physical structure of the starting positions on the saltmarsh–mangrove interface was similar, being dominated by an exposed mud/sandy shore with few *A. marina* pneumatophores and little herbaceous vegetation (<2% foliage projected cover of either *S. virginicus* or *S. quinqueflora* estimated within 100 m²). The structure of the exposed mud/sandy shore was a typical feature and generally occurred in a band of between 2 and 10 m width, where the saltmarsh–mangrove interface was clearly developed. The zone was also relevant as a starting point for fruit release since propagules from parent *A. marina* trees naturally fell in it.

Groups of propagules were placed at the starting positions approximately 6 h prior to onset of the predicted (Queensland Department of Transport, 2001) highest high tide for a particular day that was expected to be either a non-flood (2.25–2.38 m) or flood

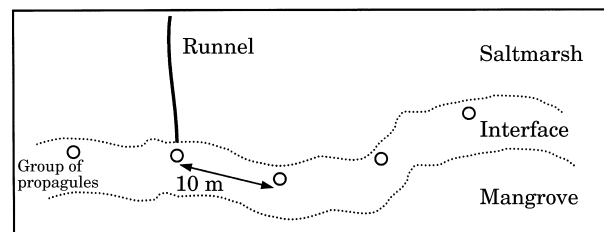


Fig. 2. Hypothetical starting positions for five groups of marked propagules. Starting positions are situated relative to the saltmarsh–mangrove interface, the runnel and each other.

(2.42–2.56 m) event. Non-flood tides in the range of 2.25–2.38 m accounted for approximately 16% of annual tidal events and reached the saltmarsh–mangrove interface, but did not inundate the saltmarsh. Tidal flood events accounted for approximately 7% of annual tides and breached the saltmarsh, extending at least 50 m up the shore onto the saltmarsh. At each of the three sites, propagules were released during a single flood and non-flood predicted high tide. The flood and non-flood tidal levels occurred during fruit abscission of *A. marina* and were included in the experiment to test the consistency and pattern of propagule deposition onto saltmarsh.

Propagule transport was monitored during the high tide, where possible, until a final point of stranding was marked on the marsh. Stranding was deemed to occur once the tide had receded below the saltmarsh–mangrove interface. Stranding positions were marked by flagging the points with small, numbered pegs. The effort required to recover marked propagules was minimized by observing their progress during daytime high tides. However, a standardized method was employed when the highest high tide occurred at night and searching was conducted the following morning. First, the marsh area was quickly surveyed to establish patterns of wrack deposition that were likely to also contain marked propagules. Once identified, searching was restricted to the wrack (strand) line and areas lower on the shore but still in the direction of tidal ebbing flow. This method concentrated the search effort to key areas at each release site and maximized the chances of recovering the majority of marked propagules.

2.4. Statistical analyses

We tested for any effects of tide (flood or non-flood) or starting position (proximity to runnel) on the proportion of propagules recovered using a two-way analysis of variance (ANOVA), with proportions being arcsine transformed prior to the analyses. Data were then treated by site and tidal period using one-way ANOVA to test the distance the marked propagules were transported up the shore; distance transported across the shore; and distance between the point of origin and final stranding. Where significant differences were detected in the one-way ANOVA, Tukey's tests (HSD) were used to identify as to which groups of propagules differed.

3. Results

A total of 444 marked propagules, in 30 groups, were released at the three sites, and 84.7% of the propagules were successfully recovered after one high tide. The proportion of propagules recovered was not influenced by tidal amplitude or starting position relative to a

runnel (two-way ANOVA: tide $df = 1, 26, P > 0.1$; runnel $df = 1, 26, P > 0.5$; interaction $df = 1, 26, P > 0.5$).

The pattern of propagule transport and final stranding on the saltmarsh varied markedly between groups released at the three sites for both tidal events. Significant differences were detected with one-way ANOVA ($P < 0.05$) among groups of propagules transported up the shore, across the shore and from the starting position at all sites and tidal events except the non-flood release at Tingalpa Site 2.

For each flooding tide, sampled groups of propagules were always transported significantly farther up the shore and from the starting position by runnels than by natural tidal influences (Table 1). A similar result occurred for the non-flooding tidal event at two of the three sites (Table 1). Thus, the point along the saltmarsh–mangrove interface at which marked propagules were released determined the extent of movement up the shore and from the starting position at each site regardless of tidal flooding.

Runnel path and position on the shore strongly influenced the transport of some propagules across the shore (Fig. 4). When two runnels were on the shore, one perpendicular to the saltmarsh–mangrove interface and the other built across the marsh (along a 30-m wide arc), propagules transported by the latter were carried significantly farther across the marsh shore (runnel group 5 in Table 1 and Fig. 4) after both tidal events, while those from the former were not (runnel group 3 in Table 1 and Fig. 4).

Groups of propagules released within 10 m of a runnel were transported significantly farther up the saltmarsh (Table 1) than any other groups released along the saltmarsh–mangrove interface (Figs. 3 and 4). However, runnel transport was not exclusive to groups located close to the structure as some propagules released 20 m away were carried to similar shore positions as those in the runnels (Table 1; see group 1 in Fig. 3).

Table 1
Summary of results from Tukey's HSD test between groups of propagules

Site	Tide	Variation: distance		
		Up shore	Across shore	From start
Tingalpa 1	Flood	1 ^a 4 ^{ab} 2 ^b 5 ^{bc} 3 ^c	3^a1^a4^a2^a5^b	1 ^a 4 ^a 2 ^a 3 ^b 5 ^c
	Non-flood	1 ^a 2 ^a 4 ^{ab} 3 ^b 5 ^c	3^a1^a4^a2^b5^c	2 ^a 1 ^{ab} 4 ^{bc} 3 ^c 5 ^d
Tingalpa 2	Flood	5 ^a 2 ^a 4 ^{ab} 1 ^{bc} 3 ^c	1 ^a 3^{ab}4^{ab}2^{ab}5^b	5 ^a 2 ^{ab} 4 ^{ab} 1 ^b 3 ^b
	Non-flood			
Coomera	Flood	3 ^a 4 ^a 5 ^a 1 ^a 2 ^b	1 ^a 2^b3^c4^d5^e	4 ^a 5 ^a 3 ^a 1 ^a 2 ^b
	Non-flood	1 ^a 3 ^a 4 ^a 5 ^a 2 ^b	1 ^a 3 ^a 4 ^a 5 ^a 2 ^a	1 ^a 3 ^a 4 ^a 5 ^a 2 ^b

Groups are ordered by means, in ascending order. No results are shown for the non-flood tide at Tingalpa Site 2 as ANOVA recorded no significant difference.

Dissimilar superscript denotes significant difference ($P < 0.01$); runnel group(s) in bold.

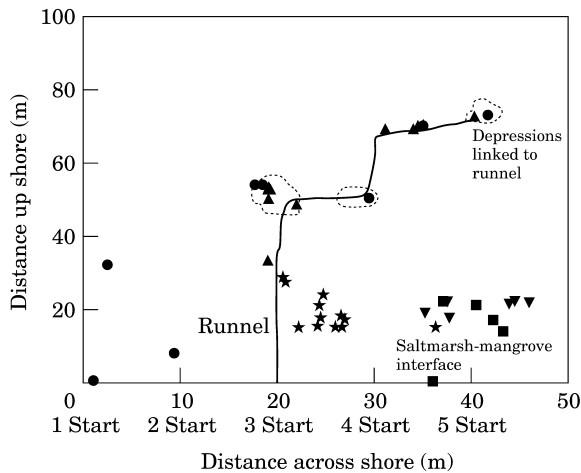


Fig. 3. Results of propagule transport after one flooding high tide (2.56 m predicted) at Tingalpa Creek Site 2. The saltmarsh–mangrove interface represents a dynamic shoreline but is simplified in the figure. Starting positions for groups of propagules were at '0' on the Y-axis. Depressions, once isolated mosquito-breeding pools, linked to runnels are shown. Symbols: ●, group 1; ★, group 2; ▲, group 3; ▼, group 4; ■, group 5.

The final stranding positions of propagules transported by runnels varied with site and tidal phase. In Figs. 3 and 4, runnels were constructed to a maximum onshore height of approximately 80 m from the saltmarsh–mangrove interface to link isolated mosquito-breeding pools located at shore heights of between 60 and 80 m. Following predicted flooding tides, propagules were not deposited in clumps, but were distributed over distances of up to 60 m (see group 5 in Fig. 4). In

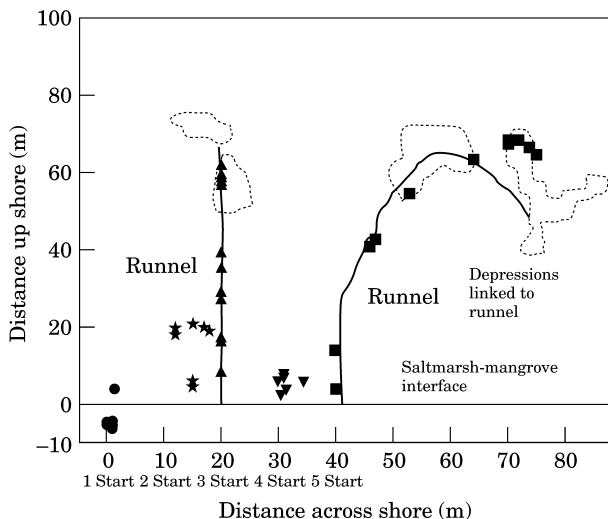


Fig. 4. Results of propagule transport after one flooding tide (2.44 m predicted) at Tingalpa Creek Site 1. Two runnels were present at the site and their connection to linked depressions is shown. Starting positions for each group of propagules were at '0' on the Y-axis, also shown as the saltmarsh–mangrove interface. Symbols: ●, group 1; ★, group 2; ▲, group 3; ▼, group 4; ■, group 5.

many cases, propagules were deposited along the edges of (former) isolated pools, now depressions, which were linked to the runnel rather than within the main channel of the runnel.

For groups of propagules not influenced by runnels, the pattern of deposition across the shore after one tidal phase was not consistent for the three sites. Some groups were deposited nearly 50 m from their original release position (Fig. 3) while groups in Fig. 4 remained within 10 m even after a flooding tide. While propagule distribution across the shore was generally varied, the distance propagules were deposited up the shore by flooding tides was restricted to approximately 20 m from the saltmarsh–mangrove interface (Figs. 3 and 4) and was consistent with observed strand lines that formed after tidal ebb.

4. Discussion

The fate of marked propagules released at each of the three sites was clearly influenced by the presence of runnels. Propagule transport was significantly different among marked groups at all sites and tidal phases except for the non-flood release at Tingalpa Creek Site 2. Dynamic environmental and physical conditions during the non-flood tide most likely affected the pattern of propagule deposition at Tingalpa Creek Site 2 apparent at all other release sites. In explanation, the shoreline at Tingalpa Creek Site 2 was not clearly defined and the width of the saltmarsh–mangrove interface extended 50 m landward in some places. Strong onshore winds and tidal flow transported some propagules to this region of the shore which was laterally similar in height to runnel-transported propagules, but was an extension of the intertidal boundary and not saltmarsh.

Runnels enable propagule transport onto saltmarsh and may increase deposition of fruit that fall from some *A. marina* on the saltmarsh–mangrove interface. In southeast Queensland, propagules generally fall during a 3-month period from August to November and, as with other described populations (Clarke, 1993; O'Grady, McGuinness, & Eamus, 1996) establish close to parent *A. marina*. During the fruit-fall period, few propagules are naturally deposited onto saltmarsh because of a lack of suitably high tides that breach the saltmarsh–mangrove interface. However, because runnels carry low-amplitude tides, which would not normally flood saltmarsh they potentially increase landward transport and deposition of propagules that fall from *A. marina* located close to the structures.

The deposition of propagules after flooding and non-flooding tidal phases was restricted to approximately 20 m up the shore from the saltmarsh–mangrove interface and was only exceeded by propagules transported by runnels which reached shore heights of up to 80 m.

The fate of propagules that were not influenced by runnels was unpredictable and in some cases, resulted in their stranding below the original release position (and close to the natural intertidal limit of *A. marina*) or not moving at all from the release position. Common saltmarsh plants such as *S. virginicus* can grow on the landward edge of the saltmarsh–mangrove interface and often form dense clumps reaching heights of 40 cm. Tides that do not completely inundate plants such as *S. virginicus* will fail to advance propagules beyond the obstruction whereas runnels are devoid of vegetation and can carry propagules unimpeded.

Observations from other saltmarshes in southeast Queensland and northern New South Wales support the findings from this experiment. For example, Dale et al. (1989) described manual removal of *A. marina* seedlings from runnels as an ongoing annual maintenance exercise. The varied size-range of seedlings and mature mangrove trees observed at some runnelled saltmarshes also suggest episodes of propagule deposition and establishment over a temporal scale consistent with the age of runnels. Few authors have reported on the long-term success of tidal-borne *A. marina* propagules on Australian saltmarsh. However, in caged experiments on saltmarsh, Clarke and Myerscough (1993) noted the failure of propagule establishment because of desiccation and Clarke and Hannon (1967, 1971) and Adam (1995) discussed the influence of salinity and water-logging on mature plant survival. Given the fact that runnels alter the hydrological patterns governing substrate salinity and porosity in restricted areas of saltmarsh, it is likely that they also create favourable growing conditions for *A. marina*, which would otherwise fail to establish.

In a colour infrared photographic comparison of a runnelled saltmarsh, Dale, Chandica, and Evans (1996) reported no direct effects of runnelling on *A. marina* expansion into the saltmarsh at Coomera Island. However, their study did describe isolated increases in mature *A. marina* density and distribution along sections of the runnel and within (former) mosquito-breeding pools linked to the runnel and tidal source (Dale et al., 1996). The increased density of *A. marina* was not statistically significant (Dale et al., 1996), but was most likely due to the transport (and later establishment) of mangrove propagules, following runnel construction, consistent with the pattern of distribution of marked propagules in this study. In addition, qualitative observations at some runnelled sites suggest that once an individual *A. marina* establishes in a depression high on the saltmarsh, its pneumatophores quickly develop in the runnel and inhibit further upshore transport of propagules carried from the saltmarsh–mangrove interface. The ‘pneumatophore filter’ may also reduce passage of propagules from the primary mangrove, thereby encouraging establishment of seedlings originat-

ing from a single localized *A. marina*. O’Grady et al. (1996) discussed similar localized recruitment episodes based on physical limitations to propagule supply and establishment and further, noted the implications for genetic transfer between these mangrove populations.

Runnel function for mosquito control requires construction of a graded conduit linking isolated mosquito-breeding pools with the tidal source so that the frequency of tidal inundation and flushing is increased. At the sites investigated in this study runnels also connected areas of *A. marina* propagule production adjoining the saltmarsh–mangrove interface to areas of the saltmarsh normally inundated by only the highest spring high tides.

Saintilan and Williams (1999) reviewed the available literature concerning mangrove transgression into saltmarsh along the eastern Australian coast. Although transgression facilitated by runnels was never forwarded in explanation of the phenomenon their conclusions highlight significant losses of saltmarsh areas to mangrove where substrate, tidal, nutrient or sedimentation conditions are altered (Saintilan & Williams, 1999). In effect, the results of this study demonstrate that propagules located close to the runnel were consistently transported to areas high on the saltmarsh shore where they would not normally be deposited. This would encourage landward extension of *A. marina* at runnelled sites, with saltmarsh losses. It could even be a useful mechanism for revegetation projects where mangrove has been denuded. The implication of this study is that the effect of runnel function on mangrove transgression is likely to be long-lasting and should be considered in future management of intertidal ecosystems where runnelling is the intended technique for mosquito control.

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