The impact of encroachment of mangroves into saltmarshes on saltwater mosquito habitats

Pat Dale^{1,2}, Leila Eslami-Andargoli^{1, 2}, Jon Knight^{1,3}

¹ *Griffith School of Environment, Griffith University, Nathan, Brisbane, Queensland, Australia 4111.*

² *Environmental Futures Centre.*

³ *Australian Rivers Institute.*

ABSTRACT: Will mangrove encroachment into saltmarshes affect saltwater mosquito habitats? In order to address this question we need to synthesise information from two perspectives: 1) at a detailed level, the mosquitoes' habitat (primarily for mosquitoes' immature stages) within mangrove forests; 2) Changes in coastal wetland structure due to mangroves expanding into existing saltmarshes, at a more general or regional level, and the driving factors. This is a synthesis of two research projects, each adding value, to address issue Project 1) showed that mosquito larval habitat in mangroves is complex, dependent on both availability of specific internal structures and interactions of these structures with tidal events, such that not all mangroves nor all parts of a mangrove forest are suitable for the immature stages. This research was based on analysing micro-topography and tidal patterns. Project 2) showed that mangrove encroachment in eastern Australia is related to both climate (mainly rainfall) and human land use, at least over several decades. This used remotely sensed data to map mangrove spatial changes and changes to land cover together with analysis of rainfall data between 1972 and 2004.

In bringing these two aspects together A key question emerges: when mangroves encroach into saltmarshes will they *displace* saltmarsh immature mosquito habitats or will they *replace* them with mangrove ones?

We conclude that there is no simple answer: it will vary with climate change and sea level scenario and how these affect the specifics of the system. But our approach, focussing on identifying mosquito habitats and mangrove spatial changes both at the detailed level of habitats within mangroves and also at the more general level of overall mangrove spatial change, identifies the two levels of understanding required to inform wetland monitoring and management.

Keyword Index: coastal wetland, management, climate, disease, land use, *Avicennia marina*, *Aedes*.

Communications Author:

Name: Professor Pat Dale

Address: Griffith School of Environment, Griffith University, Nathan Campus,

Nathan, Queensland 4111

Email: p.dale@griffith.edu.au

Fax: +61 7 3735 6707

INTRODUCTION

Mosquitoes are significant vectors of diseases for humans. Although some diseases can be fatal, such as yellow fever, dengue and malaria, there are others that are mainly debilitating but may be fatal, such as West Nile virus, recognised in USA since 1999. Ross River and Barmah Forest viruses in Australia are generally debilitating and not fatal (Dale and Knight 2008).

Mosquitoes are found wherever the environment provides the necessary conditions for their survival. For the larval stages this means water and that often includes wetlands. Intertidal wetlands provide suitable habitat for some mosquitoes and, for human populations living near the coast, this can lead to a nuisance and health risk.

Mosquitoes that spend their immature stages in saline intertidal wetlands (saltmarshes and mangroves) include several species. In USA these include *Aedes taeniorhynchus* (Wiedemann) and *Aedes sollicitans* (Walker), which are nuisance mosquitoes and may transmit West Nile virus (Center for Disease Control and Prevention (CDC) 2009). In Australia, mangrove and saltmarsh wetlands provide habitats for *Aedes vigilax* (Skuse) and *Aedes camptorhynchus* (Thomson), which are significant vectors of Ross River and Barmah Forest virus diseases in the human population (Jacups et al. 2008). Between 1993 and 2012 there was an average of 4,413 cases of Ross River and 1,246 of Barmah Forest virus diseases each year in Australia, with over 50% of each in the state of Queensland (data from Department of Health and Ageing, 2013). Mosquito management is therefore an important issue in Queensland.

Immature mosquito (eggshell and larvae) habitats in saltmarshes are relatively well documented. For example, Dale et al. (1986, 2008) showed relationships between eggshells, larvae and position in the saltmarsh landscape together with vegetation. These are related to elevation and tidal flooding patterns. Until recently it has been difficult to identify and characterise immature mosquito habitats in mangroves, as ground survey is impractical, aerial survey is impeded by canopy coverage and detailed elevation data has been lacking. Advances in the availability of high resolution LiDAR data, together with local tidal modelling, has significantly remedied this. Recent research has identified the complex tidal, elevation and habitat structures that are associated with *Ae. vigilax* larval habitats in mangrove systems (Knight 2011, Knight et al. 2009, 2012).

It is of concern that mangrove systems are generally encroaching into saltmarshes and this may affect immature mosquito habitats. The shift from saltmarsh to mangrove is occurring both overseas (McKee 2004) and in eastern Australia (Eslami-Andargoli et al. 2009, McTainsh et al. 1986, Saintilan and Williams 1999, Saintilan and Wilton 2001). Sea level changes are likely to affect intertidal ecosystems and scenarios for mangrove systems are uncertain, variable and need monitoring (Soares 2009). What has not been explored is the likely consequence of the advance of the mangroves for disease vector mosquito issues.

The interaction between mosquitoes and people and hence the risk of arbovirus disease transmission is related to their proximity to each other. For example, residential locations close to mosquito larval habitats (wetlands) were shown to increase the risk of Ross River virus disease in Brisbane (Muhar et al. 2000). Thus it is important to understand not only larval habitats within mangroves, but also how those habitats may change as climate, sea level and human land use change.

As an example of a generally applicable approach this paper describes the detailed within-mangrove community mosquito larval habitats as characterised by Knight (2011) and outlines recent research on the general expansion of mangrove communities in south-east Queensland between 1972 and 2004. It considers potential changes until 2031. It asks a key question: will the expansion of mangroves into saltmarshes be accompanied by an expansion of mosquito larval habitats?

MATERIALS AND METHODS

Study area

The study area (27°20'S, 153°10'E) extends over a linear distance of c 40 km from north to south and includes sites in northern Moreton Bay, south-east Queensland, Australia. It has a subtropical climate with maximum rainfall in the summer with a mean annual rainfall of 1028 mm (Australian Bureau of Meteorology). Ten intertidal sites were selected for the mangrove encroachment research (Figure 1). One of these, Glass Mountain Creek, was also used as an example of the mosquito habitat assessment.

Insert Figure 1

Within the intertidal zone the vegetation towards the seaward boundary was predominantly grey mangrove (*Avicennia marina* (Forsk.) Vierh). At higher elevations saltmarsh and bare ground predominated. The sites shared similar climate but the surrounding land cover characteristics varied, with exotic pine plantations mainly in northern area, and settlement and associated infrastructure more common to the south, closer to the state capital city of Brisbane. South-east Queensland had a population of over three million in 2011 and is experiencing rapid population growth

of 1.7 %/year (The State of Queensland (Treasury and Trade) 2013). This growth is planned to be contained within the South East Queensland Urban Footprint (Queensland Government 2009) which allows urban development close to the coast and hence close to mosquito larval habitats.

The mosquitoes

The requirements of the local saltwater mosquito, *Aedes vigilax*, are well known and were synthesised in Knight (2011) who referred to seminal publications such as Kerridge (1971) and Sinclair (1976). In summary, oviposition is onto a damp substrate, eggs need to be exposed and conditioned for at least 3 days, a hatch is stimulated by a decrease in dissolved oxygen when flooded and water needs to persist for larval development to adult emergence (around 5 days in sub-tropical summers). The species is autogenous (Hugo et al., 2003) and instalment hatching of eggs can occur with eggs remaining viable for up to 20 submersion – exposure cycles, as recorded by Sinclair (1976).

Data and mapping

Mosquito habitat identification within mangrove forests

To identify mosquito larval habitats within mangrove forests a digital elevation model and detailed tidal analysis were combined to relate topography to tidal flooding (as described in Knight et al 2009, Griffin et al 2010, Knight 2011). The tidal analysis related tides recorded at the nearest Standard Port (Brisbane Bar, 27° 22'S, 153° 10'E) to *in situ* data logger measurements of water depths over tidal events as described in Knight et al. (2009). A digital elevation model (derived from LiDAR data) at a 1 m² resolution with 0.45 m horizontal and 0.05 m vertical accuracy

was used to describe the detailed micro-topography and to model tidal flooding events (also described in Knight et al. 2009). To relate these to mosquito habitats, *Ae vigilax* mosquito eggshells were extracted from substrate samples collected and then assessed in the laboratory. Field samples of 10 cc substrate were collected from the wetland surface and around pools and depressions as described in Dale et al (2008). Laboratory analysis involved drying and sieving samples then preparing them for eggshell counting, using the method of Ritchie and Jennings (1994).

Mangrove encroachment into saltmarsh

Mangrove expansion and encroachment into saltmarsh was analysed during two periods, a relatively wet (1972-1990) and a relatively dry period (1991-2004), as established by change point analysis (described in Eslami-Andargoli et al. 2009) which identified 1990 as a significant point of change in rainfall patterns. During the wetter period (1972-1990) the mean annual rainfall was 1321 mm (median 1330 mm); in the drier period (1991-2004) it was 1062 mm (median 982 mm). The mean annual rainfall in the area is 1028 mm (median 1074) (data from the Australian Bureau of Meteorology).

Mangrove spatial changes, land cover and population changes were calculated as % change per year for each site, for both periods 1972-1990 and 1990-2004, using aerial photographs for mangrove mapping, Landsat satellite imagery for land use and Australian Bureau of Census data for population (Eslami-Andargoli et al. 2010, 2013).

The perimeter-to-area relationship was calculated as a Mangrove-Saltmarsh Interface (MSI) index for each site. This showed the relationship between mangrove area and its boundary with saltmarsh. In theory, other things being equal, the greater

the value of the index the greater the potential for mangroves to spread into saltmarsh (Eslami-Andargoli et al. 2010).

Analysis

Mosquito larval habitats

At the local level, relevant to mosquitoes, the internal structure of the mangrove system was described using the detailed LiDAR elevation data. Tidal data from *in situ* loggers were used to model the patterns of flooding and hence the likelihood of mosquito egg hatch and larval survival. To do this, thresholds of flooding across the mangrove and the frequencies of whole system flooding were established by comparing tides at the fringing edge of the mangroves with elevations within the system (berm and basin). Based on the habitat requirements of immature *Aedes vigilax* this was used to identify why some habitats were particularly suitable for mosquito larval development (Knight 2012).

Mangrove encroachment - Identifying relationships

A Partial Least Square Regression (PLSR) method was used to generalise and combine features from principal component analysis and multiple regression (Abdi 2003). This technique is described in more detail in Eslami-Andargoli et al. (2010) and summarised here. It is an alternative approach to the ordinary least square (OLS) regression for handling data that may exhibit high dimensionality and multicollinearity. It is especially appropriate for ecological analysis, as ecological phenomena are frequently described by many variables which may not be independent. Also, the method can be used where there are many predictors compared to the number of observations (Carrascal et al. 2009).

Predicting mangrove spatial changes

As a hypothetical exercise we attempted to predict potential change scenarios in mangrove distribution over 27 years until 2031. That is the time frame for the South East Queensland Regional Plan (Queensland Government 2009). There were two scenarios: one assumed a rate of change similar to that in the ‘wetter’ period; the other was based on the ‘drier’ period. For example at the Glass Mountain Creek site the average annual rate of change in the wetter period was 2.15% and during the drier period it was 1.02%. These figures were used to calculate the area expected in 2031.

To assess the potential effect of population and urbanisation growth in the coastal zone, the Urban Footprint that constrains development (South East Queensland Regional Plan) was inspected to see if urban encroachment, particularly towards the coast, would be likely to have an impact on mangrove expansion. This was a qualitative assessment.

Integrating adaptation, encroachment and internal mangrove structure

We constructed a hypothetical figure to illustrate the potential effect of two human adaptation responses to sea level rise. These were: 1) for settlement to retreat from the coast, allowing increased flooding inland; 2) to construct defences preventing flooding. This was a qualitative assessment, constructed by modifying the schematic.

RESULTS

Mosquito larval habitats

The micro-topography analysis identified three landscape units in the mangrove system. Figure 2 shows a schematic of these units as well as indicating the upslope saltmarsh and upland human settlement. The landscape units were: 1. fringing mangroves at the seaward edge with a relatively consistent slope (i.e., no pool

structure); 2 a berm or ridge that limited tidal connections into the landward side of the site to only the 10% - 15% of high tides that exceeded the berm elevation, and 3. a shallow depression or basin on the landward side that contained pools, suitable for larvae, and with emergent sediment islands with some pneumatophores, suitable for oviposition. It is in the shallow basin areas, with pool structures that the presence of mosquito habitats were confirmed by the eggshell densities. For example, at the Glass Mountain Creek site there were on average 0.74 eggshells/cc in the shallow basin, whereas there were no eggshells in the fringing forest samples. Addison et al. (1992) showed that an eggshell density of greater than 0.05/cc indicated a mosquito problem habitat. Hydrological modelling by Knight (2011) showed that water loss due to infiltration and evapotranspiration from the basin indicated that water would generally remain long enough for larvae to develop to adult emergence at that site.

Insert Figure 2

Mangrove expansion

Overall between 1972 and 2004 mangroves generally expanded, with an increase of 119 ha at the landward edge, encroaching into and replacing 117 ha of saltmarsh. The rate of encroachment was consistent during the wetter period, when all sites experienced mangrove increase and, in all but one (Pine Rivers), this was also accompanied by saltmarsh loss. This pattern was less marked during the drier period with two sites showing a loss of mangrove and increase in saltmarsh (Hays Inlet and Little Burpengary Creek). Another site (Pine River) showing an increase in saltmarsh and no change in mangroves (Figure 3). The greatest rate of change was for Glass

Mountain Creek. There, during the wetter period, mangroves increased by 2.15% per year reducing to 1.02% per year during the drier period.

Insert Figure 3

The increases are displayed visually in Figure 4 for the Glass Mountain Creek site. The three illustrations at the top show the situation at each of the years 1972, 1990 and 2004. These show the change from salt marsh dominance in 1972 to mangrove dominance in 2004. There appeared to be no loss of mangroves at the tidal edge and that was consistent also for all the other sites. The expansion of mangroves is accentuated in a lighter tone (yellow) in the two illustrations at the bottom (Figure 4). This shows that the expansion has been at the expense of saltmarsh and that it was less during the drier period.

Insert Figure 4

Predictors of mangrove expansion

The results of the PLSR analysis showed that in both the wet and dry periods there was a positive R^2 relationship ($P < 0.05$) between mangrove expansion and the other variables (Table 1). Median Rainfall and the MSI index (opportunity to expand) had the greatest influence in both wetter and drier periods, but the other variables all contributed to influencing mangrove expansion (but negatively in the case of agriculture).

Insert Table 1

Extrapolating the changes

Table 2 shows that the area of mangroves by 2013 changed from 686 ha in 2004 to 912 ha if wetter (an increase of 33%) and to 736 ha if drier (7%). If the effect of future urbanisation, as envisaged in the Urban Footprint of the South East Queensland Regional Plan, were to be added to this then the increase in mangrove area could be greater as there was a positive relationship between mangrove expansion and population density and built up area during both wetter and drier periods (Table 1). This remains a qualitative observation.

Insert Table 2

Adapting to Sea level rise

Figure 5 provides a qualitative visual representation of the current situation and the two extremes of potential human adaptation to sea level rise: retreat of settlement (allowing the system to move inland) and defence (constructing barriers to the sea). Figure 5 (a) shows the schematic with indicative settlement – this is the current situation. Figure 5 (b) shows the retreat adaptation option whereby the intertidal mangrove systems move inland, and so do the saltmarshes. With this scenario there would be a risk of increased intertidal and mosquito habitat, most likely moving closer to human settlement (depending on how retreat would be implemented). With the defence option, the scenario shown in Figure 5(c) illustrates building of, for example, sea walls. The seaward side would be under tidal water and the intertidal (and mosquito) habitat would be lost, replaced by a marine system.

Insert Figure 5

DISCUSSION

Mosquito habitats

Immature mosquito distribution in mangroves is related to micro-habitat characteristics including tidal patterns. This is widely applicable to other mangrove systems as shown by Knight et al. (2012) who found similar relationships in southern Moreton Bay and this was subsequently confirmed by similar findings, including larval and eggshell surveys, in other sites (Knight unpublished data). This supports the view that not all parts of mangrove systems are suitable for all the immature stages of *Ae vigilax*. In general, if around 10% to 15% of tides flood areas within mangrove forests, there will be habitats suitable for oviposition, hatch and larval survival. This is also consistent with Ritchie and Addison (1992). A greater percentage of flooding tides, as with sea level rise, creates a longer lasting impounding effect and would be detrimental for mosquitoes as shown in Knight (2011). It would restrict oviposition and hatch as well as allowing increased access to fish as potential predators.

Mangrove encroachment

At a regional level, mangrove systems are encroaching into saltmarshes. Saltmarshes also contain mosquito larval habitats in the pools and depressions (Dale et al. 1986). Whether the saltmarsh oviposition and larval habitats will become mangrove ones remains speculative. Saltmarsh topography (with local pools and relatively small depressions) may be transformed into problem mosquito habitats as mangroves encroach. Conversely saltmarsh pools may become deeper and act as

refuges for resident fish and hence sustain fewer mosquito larvae. The likely situation is uncertain.

Climate and sea level change

Another factor is the uncertain impact of climate change. In the south-east Queensland area of the research, climate change is anticipated to result in less rainfall with more dry days (Burton et al. 2009). As shown in Figure 3 and Table 2 this would be likely to result in a reduced rate of expansion and sometimes in a loss of mangroves. In that scenario, although mosquito larval habitats may not change a great deal, mosquitoes might still pose an increased health risk. This is because predicted increases in temperatures can speed up development of the immature mosquito stages, virus replication and also potentially extend the problem season (during the warmer months). This aspect of arboviral disease is discussed in more detail in (Weaver and Reisen 2010).

Sea level changes are also likely to impact the intertidal systems, especially in the longer term. For example Traill et al. (2011) modelled the effect of sea level rise on coastal vegetation in the southern part of Moreton Bay, Queensland, until 2100. They used two scenarios: a conservative rise of 0.64 m and a worst-case scenario of a rise of 1.80 m. For the conservative prediction they estimated a loss of 33% of saltmarsh and a gain of 35% of mangroves. This may represent the scenario whereby mangrove habitats replace saltmarsh ones. For the extreme scenario there would be a 19% loss of mangroves and a 98% loss of saltmarsh. In that scenario mosquito habitats would be reduced. In our research we found no change in the extent of mangroves at the seaward edge over the 18-year period, indicating that mangroves in the area were not

being lost to the sea, at least in decadal time-frames. This may reflect a process of sediment accumulation and there are data that suggest an accumulation rate of ~5 mm/year over the last 100 years in 2 mangrove sites in the general area (Knight unpublished data). Sea level is generally rising in the area at a rate of 3.1 mm/year (Burton et al. 2009). Nevertheless, there is considerable uncertainty, with outcomes dependent on the various models used. For example, Oliver et al. (2012), for the south-east coast of New South Wales, Australia, predicted virtually 100% mangrove cover by 2100 under one sea level rise model but most of the area under water in another.

In summary, sea level rise scenarios may result in a range of mosquito related responses. They include: increased mosquito problems, for example if mangrove basins replace saltmarsh larval habitats; reduced mosquito problems, for example if the intertidal areas remain wet, inhibiting mosquito egg conditioning; or no problems from saltwater mosquito species if inundation is more or less complete (one of the scenarios in Oliver et al. 2012).

Management

Management needs to have regard to the uncertainty of ecological responses to climate and sea level changes. Planning time-frames for human adaptation to the changing intertidal environments are also important. Rather than attempting to adapt to end-of-century scenarios, the planning time-frame realistically needs to look forward for a few decades, for example within the 2031 planning horizon of the South East Queensland Regional Plan (at least for south-east Queensland, as we have used here). Models by Oliver et al. (2012), for eastern Australia showed large variations by 2100, but, whichever model they applied, the changes by 2030 were relatively minor.

From a human health perspective the key questions that remain are: will encroaching mangroves, around areas of increasingly dense human settlement, result in an increased or decreased mosquito problem? How can mosquito control and urban planning help reduce the risk of arbovirus disease transmission?

It is beyond the scope of this paper to address the human land use planning issue, but population and land use are also drivers of mangrove encroachment into saltmarshes, especially when close to the wetlands (e.g., Eslami-Andergoli et al. 2013). Land use planning in Queensland under the Sustainable Planning Act (2009) is supposed to manage the ‘effects of development on the environment’ (Section 3(b)). Environment is broadly defined and so includes issues of both ecosystems and human health. Effective management to conserve ecosystem and human health needs collaboration between planning and mosquito agencies (Muhar and Dale 2001) and needs to be developed as a priority action.

CONCLUSION

The question raised at the start was: will mangrove encroachment into saltmarshes affect saltwater mosquito habitats? To address this we have synthesised research findings at two levels of resolution. At the detailed level, the internal structure of mangroves relates to mosquito larval habitats and, at the general level, mangrove encroachment into saltmarshes has the potential to replace saltmarsh mosquito habitats with mangrove ones. This is a general pattern in Australia and overseas. The simple conclusion is that mangrove encroachment into saltmarshes will have implications for mosquito populations. There is uncertainty as to the detailed effects in specific locations and each will, at least for the present, need to be monitored and addressed on a case-by-case basis, supported by resources and capacity building. The synthesising approach adopted here has the potential to inform and guide management

in an environment of change. Specifically, mosquito management, which is locally implemented, needs to be integrated with land use planning systems, which often operate at a more general level.

ACKNOWLEDGEMENTS

This research was supported by data provided by State and National agencies in Australia, by in-kind provision of facilities by Griffith University and Eslami-Andergoli was supported by Tehran University.

REFERENCES

- Abdi, H. 2003. Partial Least Squares (PLS) Regression. *in* M. Lewis-Beck, A. Bryman, and T. Futing editors. Encyclopedia of Social Sciences Research Methods. Thousand Oaks (CA), Sage.
- Addison, D., Ritchie, S., Webber, L., Essen, F.v., 1992. Eggshells as an index of aedine mosquito production 2: relationship of *Aedes taeniorhynchus* eggshell density to larval production. J Amer. Mosq. Cont. Assoc. 8: 38-43.
- Burton, D., K. Mallon, P. Taygfeld, E. Laurie and L. Bowra. 2009. Climate Risk report -Scoping Climate Change Risk for Moreton Bay Regional Council (MBRC). 82pp. avilable on-line:
<http://www.moretonbay.qld.gov.au/uploadedFiles/moretonbay/environment/Scoping-Climate-Change-Risk.pdf> Accessed 3 July 2013
- Carrascal, L. M., I. Galván and O. Gordo. 2009. Partial least squares regression as an alternative to current regression methods used in ecology. 18: 681-690.
- Center for Disease Control and Prevention (CDC) Division of Vector-Borne Diseases (2009) West Nile Virus.
<http://www.cdc.gov/ncidod/dvbid/westnile/mosquitoSpecies.htm#99>

Accessed 29 April 2013

Dale, P.E.R., K. Hulsman, D. Harrison, and B Congdon. 1986. Distribution of the immature stages of *Aedes vigilax* on a coastal salt marsh in South East Queensland. Aust. J. Ecol. 11: 269-278.

Dale, P. E. R. and J. M. Knight. 2008. Wetlands and mosquitoes: a review. Wetl. Ecol. Mgt. 16: 255–276.

Dale, P. E. R. and J. M. Knight, B.H. Kay, H. Chapman, S.A. Ritchie and M.D Brown. 2008. Habitat characteristics and eggshell distribution of the salt marsh mosquito, *Aedes vigilax*, in marshes in subtropical eastern Australia. 8pp. J. Insect Sci. 8:25, available online: insectscience.org/8.25

Department of Health and Ageing (2013) National Notifiable Diseases Surveillance System. <http://www9.health.gov.au/cda/Source/CDA-index.cfm> Accessed April 30 2013

Eslami-Andargoli, L., P. E. R. Dale and N. Sipe. 2013. Does spatial scale affect the pattern of mangrove change under different rainfall regimes? An example in southeast Queensland, Australia. Austral Ecol, 38: 208-218

Eslami-Andargoli, L., P. E. R. Dale, N. Sipe and J. Chaseling. 2010. Local and landscape effects on spatial patterns of mangrove forest during wetter and drier periods: Moreton Bay, Southeast Queensland. Estuar. Coast. Shelf Sci. 89: 53-61.

Eslami-Andargoli, L., P. E. R. Dale, N. Sipe and J. Chaseling. 2009. Mangrove expansion and rainfall patterns in Moreton Bay, southeast Queensland, Australia, Australia. Estuar. Coast. Shelf Sci. 85: 292-98.

- Griffin, L. F., J. M. Knight, and P. E. R. Dale. 2010. Identifying Mosquito Habitat Microtopography in an Australian Mangrove Forest Using LiDAR Derived Elevation Data. *Wetlands* 30:929-937.
- Hugo, L. E., B. H. Kay and P. A. Ryan. 2003. Autogeny in *Ochlerotatus vigilax* (Diptera: Culicidae) from Southeast Queensland, Australia. *J Med. Entomol.* 40: 897-902.
- Jacups, S. P., P. I. Whelan, and B. J. Currie. 2008. Ross River virus and Barmah Forest virus infections: A review of history, ecology, and predictive models, with implications for tropical northern Australia. *Vector Borne Zoonotic Dis* 8:283-297.
- Kerridge, P., 1971. Aspects of the Ecology and biology of the Salt-Marsh Mosquito *Aedes Vigilax* (Skuse). MSc Thesis, School of Biological Sciences. University of Queensland, Brisbane, p. 197.
- Knight, J.M. 2011. A model of mosquito-mangrove basin ecosystems with implications for management. *Ecosystems* 14:1382-1395.
- Knight, J.M, L. Griffin, P.E.R. Dale and S. Phinn. 2012. Oviposition and larval habitat preferences of the saltwatermosquito, *Aedes vigilax*, in a subtropical mangrove forest in Queensland, Australia. *J. Insect Sci.* 12:On line : insectscience.org/12.16.
- Knight, J. M., P. E. R. Dale, J. Spencer, and L. Griffin. 2009. Exploring LiDAR data for mapping the micro-topography and tidal hydro-dynamics of mangrove systems: An example from southeast Queensland, Australia. *Estuar. Coast. Shelf Sci.* 85:593-600.

- McKee, K. L. 2004. Global Change Impacts on Mangrove Ecosystems.
U.S.Department of the Interior, U.S.Geological Survey.
- McTainsh, G., B. Iles and P. Saffigna. 1986. Spatial and temporal patterns of mangroves at Oyster Point Bay South East Queensland, 1944-1983. *Proc. R. Soc. Qld.* 99: 83-91.
- Muhar, A. and P.E.R. Dale. 2001. Minimizing impacts of mosquito management in ecologically sensitive urban areas: a multi-scale approach. In: *Nature Conservation 5* (eds J.L. Craig, M. Mitchell and D. Saunders) pp. 448-55. Surrey Beatty and Sons, Chipping Norton, NSW, Australia.
- Muhar, A., P. Dale L. Thalib and E. Arito. 2000. The spatial distribution of Ross River Virus infections in Brisbane: significance of residential location and relationships with vegetation types. *Environ. Health Prev. Med.* 4: 184-9.
- Murray, A. B., M.A.F. Knaapen, M. Tal and M.L. Kirwan. 2008. Biomorphodynamics: Physical-biological feedbacks that shape landscapes. *Water Resour Res* 44: W11301, doi:[10.1029/2007WR006410](https://doi.org/10.1029/2007WR006410).
- Oliver, T. S. N., K. Rogers, C.J. Chafer and C.D. Woodroffe. 2012. Measuring, mapping and modelling: an integrated approach to the management of mangrove and saltmarsh in the Minnamurra River estuary, southeast Australia. *Wetl. Ecol. Mgt.* 20: 352-71.
- Queensland Government. 2009. South East Queensland Regional Plan 2009-2031. Queensland Department of Infrastructure and Planning, Brisbane, Queensland.
- Queensland Government. 2012. Queensland Coastal Plan State Planning Policy 3/11 Guideline: Coastal Protection. Department of Environment and Resource Management, Brisbane, Queensland.

- Ritchie, S. A. and D. S. Addison. 1992. Oviposition preferences of *Aedes taeniorhynchus* (Diptera: Culicidae) in Florida mangrove forests. *Environ. Entomol.* 21: 737-744.
- Ritchie, S. A. and C. D. Jennings. 1994. Dispersion and sampling of *Aedes vigilax* eggshells in Southeast Queensland, Australia. *J Amer. Mosq. Control Assoz* 10:181-185.
- Saintilan N. and R.J. Williams. 1999. Mangrove transgression into saltmarsh environments in south-east Australia. *Global Ecology and Biogeography* 8: 117-24.
- Saintilan N. and K. Wilton. 2001. Changes in the distribution of mangroves and saltmarshes in Jervis Bay, Australia. *Wetl. Ecol. Mgt.* 9: 409–20.
- Sinclair, P., 1976. Notes on the biology of the salt-marsh mosquito, *Aedes vigilax* (Skuse) in south east Queensland. *Qd. Nat.* 21, 134-139.
- Soares, M. L. G. 2009. A Conceptual Model for the Responses of Mangrove Forests to Sea Level Rise. *J Coastal Research. Special Issue* 56: 267-271.
- The State of Queensland (Office of Treasury and Trade). 2013. Population and Dwellings, South East Queensland.
www.oesr.qld.gov.au/products/profiles/.../pop-housing-profiles-seq.pdf viewed 7th May 2013
- Traill L. W., K. Perhans, C.E. Lovelock, A. Prohaska, S. McFallan, J.R. Rhodes and K.A. Wilson. 2011. Managing for change: wetland transitions under sea-level rise and outcomes for threatened species. *Divers Distrib.* 17: 1225-33.
- Weaver S. C. and W.K. Reisen. 2010. Present and future arboviral threats. *Antivir. Res.* 85: 328-45.

Table 1. Summary of the PLSR analysis for ten sites

Response	Predictor variables						R ²
Mangrove expansion	Rain	MSI index	Pop densit y	Agriculture (%)	Built up (%)	Plantation forest (%)	
Pre 1990 - wetter	0.306	0.492	0.217	-0.485	0.054	0.200	0.913
Post 1990 - drier	0.314	0.486	0.189	-0.128	0.015	0.229	0.732

Bold indicates significant R² ($P < 0.05$)

Table 2. Predicted change in mangrove area between 2004 and 2031 based on the established rate of change during relatively wet and dry periods (rounded to nearest integer) (% change from 2004).

Site	Mangrove area 2004 (ha)	Predicted mangrove area 2031 – wet period (ha) (%)	Predicted mangrove area 2031 – dry period (ha) (%)
Cabbage Tree Ck	59	82 (39)	67 (14)
Bald Hills Ck	76	117 (54)	89 (17)
Pine Rivers	72	80 (11)	72 (0)
Hays Inlet	160	189 (18)	142 (-11)
Little Burpengary Ck	72	90 (25)	66 (-8)
Burpengary Ck	20	31 (55)	25 (25)
Southern Caboolture	88	123 (40)	100 (14)
Lagoon Ck	44	49 (11)	52 (18)
Ningi Ck	35	47 (34)	46 (31)
Glass Mt Ck	60	104 (73)	77 (28)
TOTAL	686	912 (33)	736 (7)