# An Australian form of Open Marsh Water Management (runnelling): long term monitoring, ancillary and extended research

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**Title Page**

Title: An Australian form of Open Marsh Water Management (Runnelling): long term monitoring, ancillary and extended research.

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Title: An Australian form of Open Marsh Water Management (Runnelling): long term monitoring and ancillary research.

**Abstract** The paper outlines the evolution of an Australian form of Open Marsh Water Management (OMWM) called runnelling which was implemented in relatively pristine saltmarshes. Runnelling involves shallow channels and was distinguished from OMWM which involves ditching. Both methods aim to conserve tidal hydrology. The core research covers 28 years of research on the original experimental site (Coomera Island, Queensland), in routine monitoring and impact assessments that were made periodically. It also introduces and incorporates information from associated research. This includes effects of runnelling on non-target aspects– snails and crabs. Emerging issues during the course of the longer-term research included the risk of mobilising acid sulfates and of mangrove encroachment into the saltmarsh. As well, use of the data was extended to retrofit it to address broader questions about saltmarsh processes and how to identify them. That identified progressive changes at the Coomera site, and so a further query was whether the system showed signs of approaching a tipping point. In summary, there were some identifiable effects of runnelling in all parts of the research. These were mostly related to the increased wetness near runnels, as flooding by tides would occur at tides up to 0.30 m lower than the pre-runnelling situation. The increased wetness was related to plants, snails and crabs. From a mosquito management perspective the method was successful. From an environmental perspective the environmental changes were only very close to runnels (within 10 m). The overall changes at the experimental site were consistent with other changes in eastern Australia, especially of mangrove encroachment into saltmarshes.  Once the runnelling method appeared to manage mosquitoes without damaging wetland values it was adopted widely throughout south east

Queensland, encouraged by the positive attitude of permitting agencies, but longer-term evaluation was hindered by lack of relevant records.

**Keywords** Saltmarsh, Mosquito management, Source reduction (runnelling)

## Introduction

Mosquito-borne disease is a major public health concern throughout the world (Ratnayake 2006; Swei et al. 2020). The health response usually focusses on education, personal protection and direct management of the vector. For mosquitoes with wetland habitats, direct management often includes managing the wetlands (Dale and Knight 2012). Wetland values and the need for wise management have been recognised internationally by, for example, the 1971 Ramsar Convention and its latest Strategic Plan 2016-2024 (Ramsar 2015). From the perspective of wetland ecology, mosquito management has the potential to not only manage mosquitoes and the associated wetland disservices, but also to impact wetland values and ecosystem services (Knight et al. 2017a; Knight et al. 2017b). Modern mosquito control aims to balance these issues, to minimise disservices and maximise ecosystem services. To do this, assessment of control efficacy is often also accompanied by monitoring environmental impacts.

In Australia mosquito borne viruses such as Ross River virus (RRV) cause debilitating, though not fatal diseases, incurring socio-economic costs (Ratnayake 2006). Over half of the RRV cases in Australia are recorded in the state of Queensland (Australian Government 2020), and that state has been most proactive in mosquito control. Also, mosquito control is mandatory in Queensland (but not in other states). For details see (Dale et al. 2008a; Carlson et al. 2019). From the early days, 1950s onwards, the focus of control in Queensland was on managing salt marsh mosquitoes (mainly *Aedes vigilax* (Skuse)) at the larval stage, generally using larvicides. In the 1980s a novel form of Open Marsh Water Management (OMWM) called runnelling was developed for Coomera Island (in south east Queensland (SEQ)) that utilised tidal hydrology to manage mosquito production (Hulsman et al. 1989). The runnel research project was continued for 28 years and was the impetus for an extensive body of research. This paper considers runnelling and its impacts, ancillary research and the extended research.

The aim is to analyse the process of developing, implementing, monitoring and expanding runnelling for controlling salt marsh mosquitoes in south east Queensland, Australia.  The method here is to present the research outputs from the long-term project in three areas. The first is the core research tracing the evolution of the runnelling method leading to its wider adoption. The second is for ancillary research into impacts on non-target aspects of the system. The third extends the research and retrofits the routine monitoring data to provide added scientific understanding of plant related marsh processes and the approach of a tipping point.  The projects and linkages are shown in Fig 1.

Insert Fig 1. The three areas of the research: core, ancillary and extended research.

## Core Research

First, we outline the impetus for developing a habitat modification (source reduction) method and discuss briefly why it needed to be distinct from OMWM as carried out on the eastern seaboard of USA. Then we outline the progress made in the rationale and development of a novel method, followed by a brief note on environmental impacts and longer-term assessment.

The impetus for a new or additional method of mosquito control came from a farsighted local government in south east Queensland. In 1980 it enlisted the help of researchers at the local University (Griffith) to see if there was a way to reduce the use of larvicides (at that time an organophosphate) on a trial saltmarsh site to the north of the Gold Coast, a major tourist destination (Coomera Island $27^0$ 51'S; $153^0$ 23' E). The area has a diurnal tidal cycle, with a tidal range of around 2.5 m and vegetation at the start consisted primarily of Marine couch, *Sporobolus virginicus* (L.) Kunth and Samphire, *Sarcocornia quinqueflora* Bunge ex Ung-Sternb. *Ae. vigilax* was the problem mosquito, a vector of RRV.

The rationale for a method distinct from OMWM was related to the relatively undisturbed nature of Australian intertidal saltmarshes. In contrast to at least the eastern seaboard of USA, Australia had no developed or widespread program of modifying intertidal wetlands. As a result, saltmarshes were relatively pristine, although some were subject to grazing at that time (and some still are). Thus, the use of OMWM as practised in USA was perceived to be likely to unacceptably damage the marshes and it was questioned whether the OMWM structures (relatively deep ditches) were necessary to manage the mosquito populations. The overarching aim was to devise a method to interfere with the larval life cycle, but not to jeopardise marsh ecosystem processes. The question was: what is the least that can be done to reduce saltmarsh mosquito populations in dynamic saltmarsh environments without adversely impacting the ecology of non-target features?

To address this, three years of passive research (field, remote sensing and literature) was carried out in collaboration with an interdisciplinary team of researchers, policy people and mosquito control personnel. It assessed water movement, larval distribution, eggshell distribution and used colour infrared aerial survey to provide both general and detailed habitat information (Dale et al. 1986a, b).

In 1985 a research project was proposed to construct wide shallow (<0.30 m) channels or runnels following natural water movement, to flush larvae off the marsh, to allow fish access and possibly to reduce oviposition. It was called runnelling, to avoid association with the perceived damaging effects of traditional ditching. In November 1985, after permitting, the project was constructed, by hand by a field team. Monitoring followed with quarterly surveys in the runnelled area and nearby unmodified marsh. Mosquito larval numbers, plant species and size, soil water pH and salinity and water table depth and salinity were monitored. Plants were used as they were considered to be indicators of habitat conditions and would be likely to respond to changes. An added advantage was that they could easily be located in fixed quadrats at each visit. As well, the width and depth of runnels were measured at four sites along the runnels at the same time. The early development of the project at Coomera Island and short-term impact was reported in Hulsman et al. (1989). They concluded that the method had the potential to control mosquitoes and minimize non-target effects. The monitoring of the Coomera Island project continued every 3 months for the next 20 years (until end of 2005) and then in 2008 and 2013. Its early success led to the uptake of the method throughout much of south east Queensland and in one project in Western Australia (Latchford 1997). Runnels are mainly confined to Queensland and the Western Australian project, although there has been some interest overseas. The terrain characteristics and tidal range are specific for the method, so it is limited to places that meet the requirements (relative relief < 0.50 m; tidal range of around 2.5 m to provide for water movement on and off the marsh). To our knowledge it has not been adopted in any other country.

The efficacy of runnelling to control mosquitoes was consistently high; larvae were rarely found in the area. The Coomera site was not treated with larvicides during the monitoring period and larvae reported in Dale 2008 showed significantly fewer larvae in the treatment compared to the control site. There were two or fewer larvae/dip in the runnelled area for 90% of the time (mean 1.89/dip), compared to 54/dip in the control area (Dale 2008). Additionally, there are unreported personal observations that runnels have resulted in significant reduction in chemical use or number of treatments required. The efficacy is evidenced by the broad uptake of runnelling in the 1990s, followed by the development of a dedicated runnelling machine (Santagiuliana pers. Comm., in Dale 2008) as well as reports by several local mosquito control managers that mosquito treatments were either no longer needed at runnelled sites or were much reduced. Impacts on the environment were assessed several times comparing the treatment (runnelled sites) and control sites. Analyses included traditional methods such as ANOVA and regression (Dale and Knight 2006; Dale et al. 1993; Dale 2008) and more innovative methods such as attempting to detect anomalous changes, in that case using a mixed method approach involving classification, transition matrices and Chi squared analyses (Dale and Hulsman 1988) and Markov modelling to assess the impacts of small perturbations (Dale and Dale 2002). Dale et al. (1993) also recorded increased frequency of fish in the runnelled compared to the control sites, which potentially added extra opportunity for mosquito control. Eggshell distribution was not consistently different between runnelled compared to unrunnelled sites (Dale et al. 2002; Dale et al. 2008b). A key issue for mosquito control is the cost of source reduction. This means assessing costs over a longer-term time frame than the year of construction. In USA the time to recoup costs of construction in chemical savings was estimated to be between three and seven years (Shisler and Schulze 1985). In Australia, for runnelling Dale et al. (2018) showed that the time varied between three and 10 years depending on the amount and frequency of maintenance.

The research found that there were non-target impacts from runnelling but they were generally not significant. There were general marsh changes over the 20 years. Runnels and the adjacent area were slightly wetter than the unmodified marsh. This was not surprising as even the 0.30 m runnel depth would allow lower tides to flood the runnelled area more frequently than before modification and before flooding the marsh as a whole (Breitfuss 2003a). The runnels themselves showed some erosion in the first 3-4 years but subsequently some sedimentation brought them back to a depth very similar to that at the start. At the upper part of the runnels there was no significant difference in depth between first and last three years; the lower parts of the runnels became significantly shallower but only by 4.5 cm ($F = 30.68$, df 1,22 $P< 0.0001$). A lesson was that, had the project ended after 3 years, the prediction for runnel depth would have been disturbing and very different from what eventuated. The conclusion in the final assessment, after 20 years, was that, although there were differences between the state of the treatment (runnel) and control, the trends in both were similar and probably were related more to local land use and sea level changes than to runnels.

As runnelling appeared to be effective it was widely adopted throughout south east Queensland from the mid 1990s. Local mosquito control agencies reported during the following decades that runnels continued to work, and, often with little or no maintenance. More recently (2015-2016) a broad survey was carried to see how well runnels were working in south east Queensland, several decades after they were constructed (Knight and Dale this issue). Unfortunately, several local government areas had been amalgamated in 2008, personnel had changed, so that many records were lost or could not be found. So, areas where runnelling had at least been known to have been planned were surveyed together with mosquito control personnel to see if there were signs of runnels. This resulted in 47 sites with evidence of runnels. Some 49% were apparently still functioning, as indicated by no or little other mosquito control being needed; however, 51% were not contributing to mosquito control. In some cases, it was uncertain whether the observed characteristics were indeed runnels or were only related to cattle trampling. Maintenance records were scarce but generally, where sites had been maintained, runnels were working and larvicides were not used or only rarely used. For one ‘runnel’ without maintenance the runnel continued to work, resembling a natural feature (it was known to have been runnelled, as Dale was present at construction). It is possible that others were in a similar functioning condition, but without records or recollected observation of construction this will not be known. A lesson from this is that adequate record keeping is needed for evaluating projects and that more use could be made of the scientific information from the original runnelling project (Coomera Island) in strategic and longer-term planning for other runnelling projects.

## **Ancillary Research: non-target aspects of the system**

As the runnelling project continued successfully, other environmental issues started to receive attention and were added to the project as ancillary research (Fig. 1). They were carried out by postgraduate students and staff of Griffith University, but always included the core team: the leader and the lead student assistants who ensured that the field and associated laboratory work was reliably and consistently executed. The issues included effects of modification on non-target organisms (crabs and snails), the emerging issues of mangrove encroachment and acid sulfate soils.

### Non target biota: crabs and snails

The research on non-target biota was primarily carried out by Breitfuss, contributing to the impact assessment but also to scientific method. Although his research focussed on the Coomera Island runnel site he also surveyed, for comparison, other local runnelled saltmarsh sites.  His overall conclusion was that although runnelling does affect the non-target organisms studied, it is at a restricted scale (< 10 m from runnel edge). Any effects appeared to be related to substrate conditions especially moisture, which is not unexpected, since lower tides flood more frequently into the marsh after runnelling (Breitfuss 2003a). This resulted in increased marsh wetness, at least in the vicinity of the runnels and this is also supported by the long-term monitoring (Dale 2008).

Crabs: Overall there were effects of runnelling on the common shore crabs at Coomera Island and other runnelled saltmarshes. Crab numbers were assessed at Coomera Island and other sites, based on overnight trapping, counting and releasing the crabs. The two most common crab species studied were an upper shore, drier substrate specialist *Helograpsus haswellianus* (Whitelegge, 1890) and a lower shore, wetter substrate specialist *Parasesarma erythrodactyla* Hess, 1865. There were differences for the two species between runnelled and unrunnelled sites, but these relationships also differed between the other runnelled saltmarshes. This reflects specific relationships with substrate conditions, which were affected by runnelling (wetter) and which may have differed between the marshes (Breitfuss et al. 2004a).

At a more detailed level crab size and abundance varied as indicated by burrow use and diameter size. Medium to large crabs were associated with close proximity to runnels, and smaller crabs were fewer (Breitfuss et al. 2004b). Focussing on active/inactive burrows of *H. haswellianus* in several runnelled sites (including the Coomera one) Breitfuss et al. (2004b) concluded that the influence of tidal factors was more important for crab distribution than whether runnels were present. Complementing this, the longer-term routine monitoring first noted crab burrows in the Coomera site 8 years after runnel construction. As well, Breitfuss contributed to practical scientific method for estimating crab abundance by observing that grapsid crab burrows (in this case *H. haswellianus* (Whitelegge, 1890)) in active use could be used to accurately assess crab abundance and that the method had potential for more general environmental impact assessment (Breitfuss 2003b).

Snails: The runnelled sites were wetter than the unrunnelled ones and this was also reflected in the distribution and size classes of the snails *Salinator solida* (Martens) and

*Ophicardelus* spp (Beck). Snails at Coomera showed density and size classes characteristic of those in tidal flooding periods, even during non-flooding events. Breitfuss (2003a) attributed this to soil conditions. However, the pattern was variable across two other runnelled sites also surveyed, indicating site specific factors.

In summary the conclusions from the several impacts assessments on various aspects of the system converged to a common theme: that increased wetness close to runnels was related to the difference observed between the runnelled area and the control. Nevertheless, the marsh appeared to be relatively intact at least for the first 20 years, after that, what had been a predominantly saltmarsh-dominated system became increasingly invaded by mangroves with reductions in both the cover and density of *S. virginicus* and *S. quinqueflora*. This became more apparent as the emerging issue of mangrove encroachment was explored, at the study site and more widely in south east Queensland. This shift in dominance reflects the dynamic nature of saltmarsh and mangrove interfaces.

## Emerging issues

### *Mangrove encroachment*

There was some concern at the start of the project that runnels would lead to mangrove colonisation of the higher marsh. In the early years this was not apparent and Breitfuss et al. (2003) showed that although the propagules of the Grey mangrove *Avicennia marina* (Forsk.), the dominant mangrove species locally, were transported to the higher marsh via runnels, they did not establish on the marsh, nor, at that time, in the runnels. Complementing this research Jones et al (2004) used colour infrared aerial imagery for the runnelled site and a control area to assess changes between 1987, 1991 and 1999 (i.e., 2 to14 years after modification). This was to see if they were related to runnelling. They found large increases in *A. marina* over the time period, but this was not apparently related to runnelling, but rather to changes in sea level or catchment modification. In retrospect it is interesting that mangroves were preferentially invading the succulent *S. quinqueflora* which tends to occupy low marsh positions. This was an early indicator of what has been widely recognised that mangroves are encroaching into salt marshes in eastern Australia (Saintilan et al. 2019; Saintilan and Williams 1999) and particularly in south east Queensland (Eslami- Andargoli et al. 2009, 2010). The impact of mangrove encroachment into saltmarshes on mosquito control has been discussed in Dale et al (2013). It left unanswered the question as to whether mangrove encroachment would displace saltmarsh mosquito habitats or replace them with mangrove ones. If the latter, then mosquito control would have to adapt to the emerging situation and consider if source reduction could be an option. There has been a trial source reduction project in a mangrove system in New South Wales (south of Queensland), using the same rationale as was used for runnelling (see Dale and Knight 2012).

### *Acid sulfate soils*

Acid sulfate soils contain iron sulfides and produce sulfuric acid when exposed to air. This was not recognised as a potential issue when runnels were first constructed in the 1980s. They became an issue when a huge fish-kill, in the Tweed river just south of the Queensland state border, was attributed to the use of larvicides by mosquito control. Clive Easton, who was in charge of mosquito control for the Tweed Shire Council, investigated and found that the reason for the fish kill was acid drainage from sugar cane farms that had been flooded after a very dry period. This had resulted in mobilising the potential acid sulfate soils (PASS) leading to sulfuric acid draining into the river causing anoxic conditions and killing fish

(Easton 1989). Later a system of floodgates was designed to ensure that the event would not be repeated (Easton and Marshall 2000).

In retrospect it was fortunate that the runnel project had not led to an acid sulfate issue. This is because PASS underlies much of coastal south east Queensland at elevations below 5m) (Dear et al. 2014) although they are often at depths of 0.50 m below the surface, outside the permitted depth range of runnels (0.30 m) (Alsemgeest et al. 2005). When runnels were designed for the Coomera project in 1985 the depth limit was because there was a sand layer at that depth and it was feared that, if it was penetrated, erosion would result. To check if there had been any acidity after construction, we revisited the data and found that the soil pH was on average 6.74 (SD 0.50) and never fell below pH4 (the acid sulfate action level). There were several surveys to identify PASS at both at the Coomera site and on other salt marshes (Saffigna and Dale 1999; Saffigna et al. 1997). They concluded that runnelling, with shallow channels (depth < 0.30 m), would be unlikely to disturb acid sulfate soils in the study area. Subsequently a risk assessment protocol and management plan for runnelling was devised and applied to runnel construction and maintenance to ensure that the issue of acid sulfates was not overlooked in planning source reduction (Alsemgeest et al. 2005).

## **Extended research: retrofitting the data**

The idea of retrofitting the longer-term data from field observation to analyse other issues of apparent changes in marsh processes over the decades led to two approaches; one was to investigate if marsh vegetation was in fact changing and, if so, the trajectory; the other was to see if there was any indication of an approaching state change (or tipping point).

## Marsh vegetation processes

The first analysis used the first 14 years of data (Dale and Dale 2002); the second repeated the analysis using 28 years of data: 20 years collected quarterly and then in 2005 and 2013 (Dale and Dale 2016). The plant data (size and density of the two dominant marsh species) were classified using an unsupervised Minimal Message Length (MML) method. For a clear explanation of the method refer to Wallace (2005) and for a recent review of the method see Kasarapu and Allison (2015). Each sample at each monitoring time was treated as independent for the purpose of classification (N=2460). The classification with the minimum message length was used to identify and characterise the classes (N= 13). Class numbers were assigned by the classification and have no intrinsic meaning; class descriptions came from the plant characteristics associated with each class. The classes were arranged in a transition matrix that showed how each class behaved from time to time. The change pattern was presented as a simplified figure representing the number of times each class was followed by itself or by one of the other classes, using a predetermined cut off to exclude rare transitions (Fig 2). This means that there were some infrequent connections not included in Fig. 2.

Insert Fig. 2 A simplified marsh process diagram

The classes and connections that emerged over the longer time frame, were similar to those at the 14 years analysis and identified a process of change. For example, on the left of Fig 2 there is a process whereby dense *S. virginicus* (initially the dominant vegetation) progressively became shorter and sparser until it was generally replaced by bare mud, though there was some cycling between those classes (10 and 13). On the right there is a process whereby classes containing *S. quinqueflora* vary in their size and density of both *S. quinqueflora* and *S. virginicus* until *S. virginicus* disappears from the process (Class 12). There is one connection between the two sides of Fig 2 (Classes 2 and 3).

There were some points of no return, for example on the left, once in classes 7, 10 and 13 there was no return to class 1, and on the right, once in class 12 there was usually no return to class 9. This prompted closer examination in the results data of the presence of classes over time. This showed that the classes with *S. quinqueflora,* on the right of Fig 2, ceased to exist between 1999 and 2002, except for class 12 (short sparse *S. quinqueflora*) which persisted until 2008. By 2013, after 28 years, only 4 classes identified by the classification remained. These were classes: 1 (tall dense *S. virginicus*), 2 (shorter less dense *S. virginicus),* 7 (short sparse *S. virginicus*) and 13 (bare mud). The full raw data confirms this: there were no *S. quinqueflora* plants in 2013 compared to 780 at the start of the project in November 1985; in 2013 there were only 138 *S. virginicus* plants compared to 2820 at the start. Dale and Dale (2016) also found relationships between the classes and substrate wetness and salinity and suggested that the change observed in marsh processes might be related to sea level or climate changes. Mangrove pneumatophores had been observed in the sample sites after 8 years of monitoring and this, with the research by Breitfuss, supports the idea that wetness was a factor in the changes. The changes suggest that there may be some on-going perturbation that could indicate an approaching state change or tipping point. This is considered next.

## Approaching a tipping point?

A tipping point is the point where critical thresholds are reached and the system transitions abruptly from one state to another (i.e., an abrupt change). For subtropical saltmarshes alternate system states are mangroves and mud flats where change to either is possible from saltmarsh (Knight et al. 2017b). From the previous paragraphs it is clear that the marsh had changed over the decades of observations. But the question was: was it approaching a tipping point? Early warning indicators of tipping points are documented and discussed in the literature (e.g., Eslami-Andergoli et al. 2015). One problem with early warning is that there needs to be historical data that are appropriate and at a sufficient time scale. Although that may not be available, it may be possible to retrofit existing data to obtain a glimpse of what might be to come. The 28 years of data from the Coomera project is not very long in ecological terms but it is worthwhile to see what can be done and to see if potential predictions are supported by data.

The indicators of tipping points include: slowing recovery rates, increase in autocorrelation in the variance of the state variable of the system and changes in the pattern of skewness and self-organized patchiness (Dakos et al. 2010; Scheffer and Brock 2009). For the Coomera saltmarsh suitable data showed changes in variance and increasing skewness consistent with an approaching tipping point. Eslami-Andergoli et al. (2015) noted that there may other reasons for these changes, so the issue needs to be approached with caution. However, when the 28 years of data were classified using the MML method it seems that there may be two different state changes either approaching or established (see Fig 2) one is the process from tall dense *S. virginicus* to bare ground; the other is the complete loss of the *S. quinqueflora.* This seems to be consistent with a local tipping point (and accompanied by mangrove encroachment).

## Discussion and Conclusion

The integration of several aspects of the research added value to the whole and to science generally. The projects were all situated in intertidal areas that are vulnerable to climate and sea level changes, and the resultant vegetation responses (Kelleway et al. 2017). They added to the research on mangrove encroachment (Eslami- Andargoli et al. 2009; Eslami-Andargoli et al. 2010; Oliver et al. 2012; Rogers et al. 2014; Whitt et al. 2020) especially with the longer-term analyses of processes and tipping points.

As the project started out focussed on and funded by mosquito control, this limited its scope. The ancillary research resulted from the interest in a method that appeared to work for mosquito control and that did not destroy the marsh (our main objectives at the start). More funding became available for postgraduate research, not tied to the specifics of mosquito control. Then the longer-term data set provided a 'free' resource for the two areas that were not about mosquito control at all: the marsh process model and the tipping point issue.

From a management perspective the most positive outcome is that runnelling has not destroyed any saltmarshes (as was feared by some). The worst that has happened is that some runnels may have been taken over by natural processes and regenerated so they are no longer discernible. Another point is that longer-term research is important for assessing change (and 28 years is not long in ecological terms). As noted, had the research finished after 3 years monitoring, it would probably have been concluded that runnels were going to result in significant erosion of the saltmarsh. That did not happen. Remote sensing today should be able to provide some retrospective data (back to the 1970s for Landsat) for longer-term monitoring and more recent data may be available at the detailed resolution needed for small area assessment. Finally, the one most important factor that affected everything was the increased wetness: it was related to the encroachment of mangroves and changes to crab and snail distributions. It also was not restricted to runnelling so management for mosquitoes will have to adapt to changes to mosquito habitats and environmental managers may be interested in the expansion of the runnelling rationale (do the least necessary) into mangroves as was done in New South Wales.

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Figure Captions

Fig. 1 The three areas of the research: core, ancillary and extended research

Fig. 2 A simplified marsh process diagram (the key to species symbols indicates relative size and density (number of symbols; Class numbers are also shown for reference in the text)

## Declarations

If any of the sections are not relevant to your manuscript, please include the heading and write 'Not applicable' for that section.

*To be used for life science journals + articles with biological applications*

**Funding** (Not appplicable)

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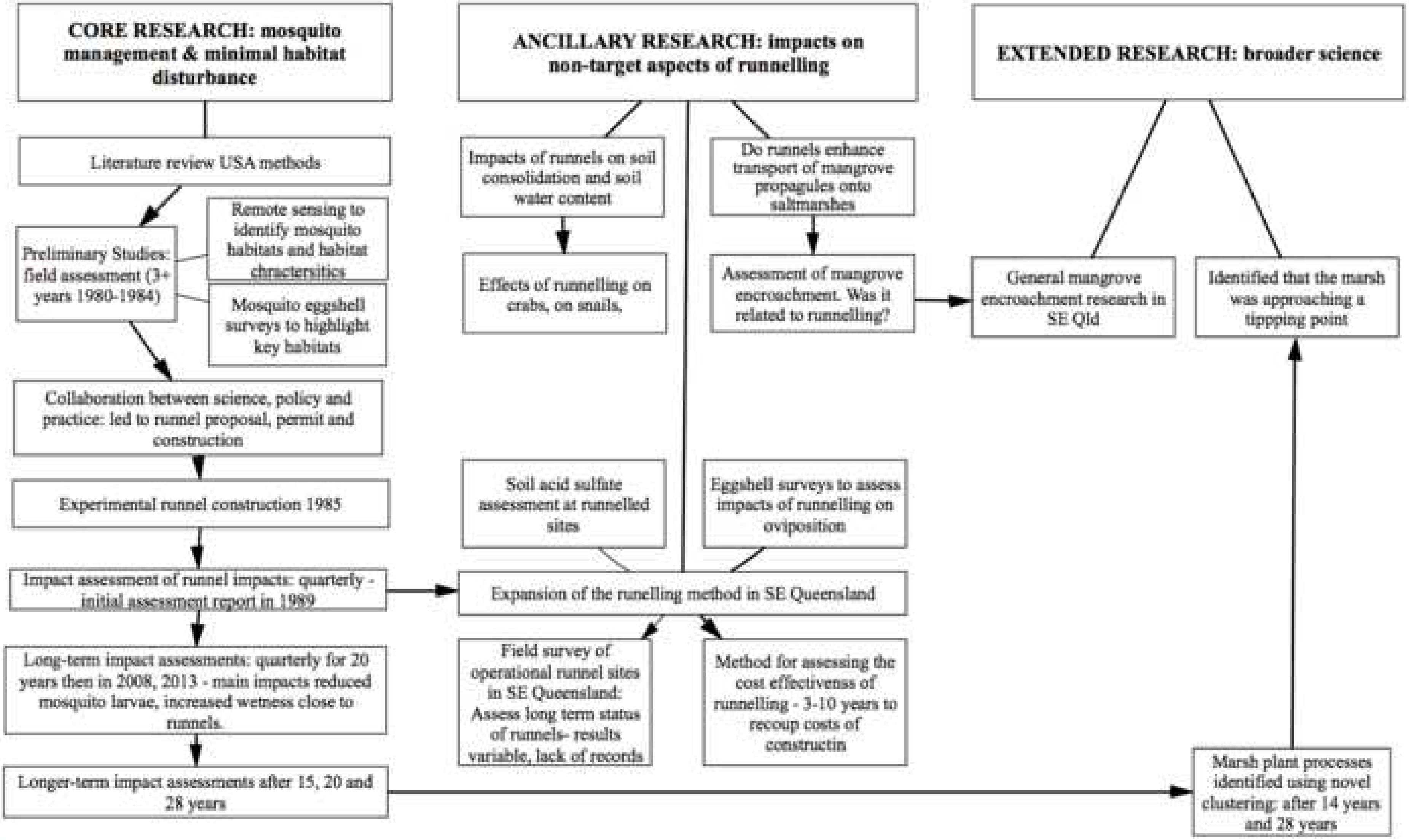
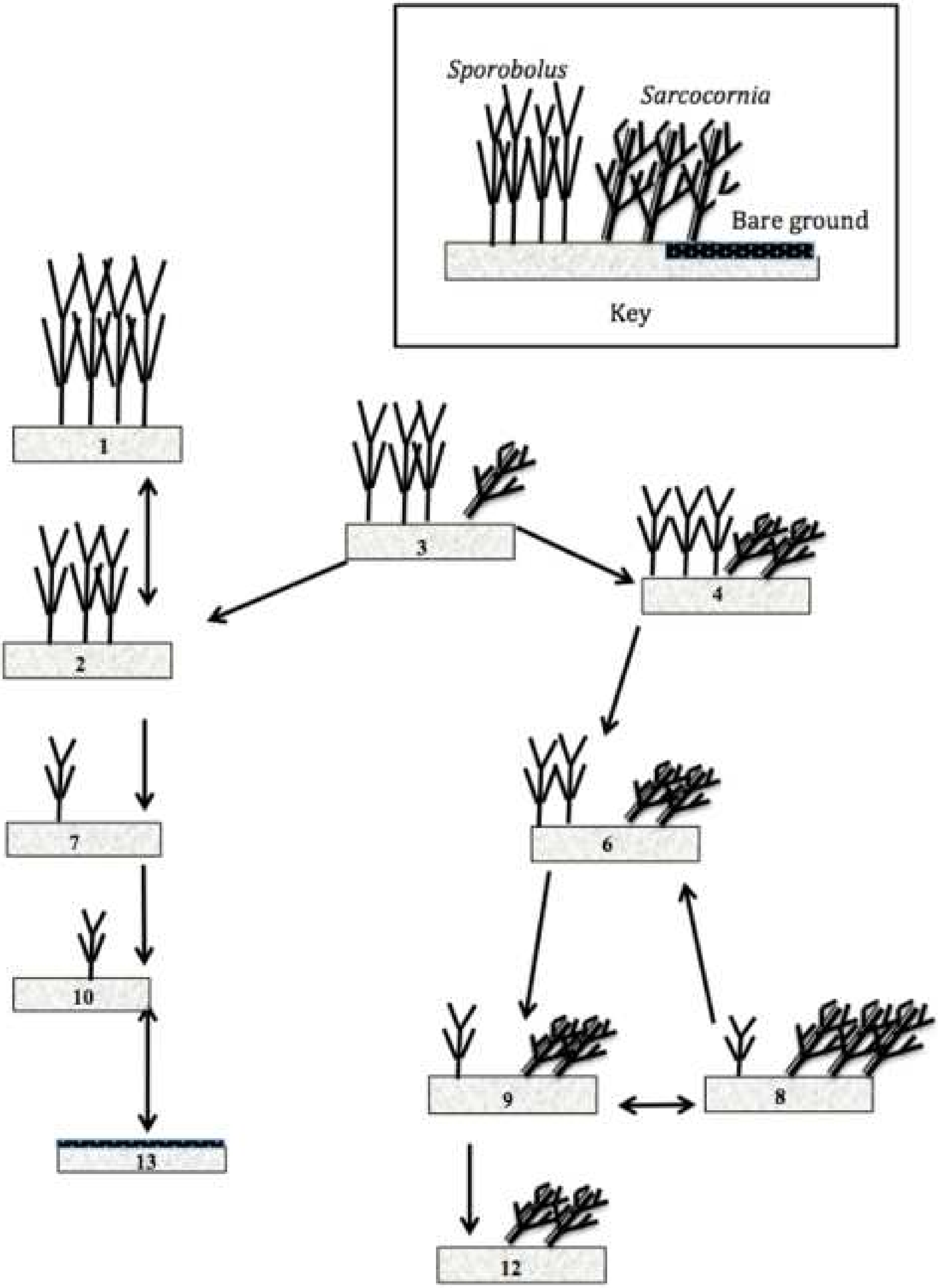

CORE RESEARCH: mosquito management & minimal habitat disturbance
ANCILLARY RESEARCH: impacts on non-target aspects of runnelling
EXTENDED RESEARCH: broader science
Literature review USA methods
Preliminary Studies: field assessment (3+ years 1980-1984)
Remote sensing to identify mosquito habitats and habitat chractersitics
Mosquito eggshell surveys to highlight key habitats
Collaboration between science, policy and practice: led to runnel proposal, permit and construction
Experimental runnel construction 1985
Impact assessment of runnel impacts: quarterly - initial assessment report in 1989
Long-term impact assessments: quarterly for 20 years then in 2008, 2013 - main impacts reduced mosquito larvae, increased wetness close to runnels.
Longer-term impact assessments after 15, 20 and 28 years
Impacts of runnels on soil consolidation and soil water content
Effects of runnelling on crabs, on snails,
Do runnels enhance transport of mangrove propagules onto saltmarshes
Assessment of mangrove encroachment. Was it related to runnelling?
Soil acid sulfate assessment at runnelled sites
Eggshell surveys to assess impacts of runnelling on oviposition
Expansion of the runelling method in SE Queensland
Field survey of operational runnel sites in SE Queensland: Assess long term status of runnels- results variable, lack of records
Method for assessing the cost effectivenss of runnelling - 3-10 years to recoup costs of constructin
General mangrove encroachment research in SE Qld
Identified that the marsh was approaching a tippping point
Marsh plant processes identified using novel clustering: after 14 years and 28 years


Sporobolus
Sarcocornia
Bare ground
Key
1
2
3
4
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