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# Environmental change over 28 years in a subtropical salt marsh: optimal classification and pictures from the exposition*

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**Abstract:** We examine monitoring data for 28 years of change in a sub-tropical salt marsh where the hydrology had been minimally modified for mosquito control. This extends the work previously published in 2002 for 14 years of data, analysed by Mike Dale (Dale and Dale 2002 *Community Ecol.* 3: 19–29). The Minimum Message Length method was used in an unsupervised classification to determine the optimum classes, based on the characteristics of the two dominant plant species: *Sporobolus virginicus* and *Sarcocornia quinqueflora.* A question at that time was whether the observed changes were only those of state (or condition) or if they were associated with a change in the underlying saltmarsh processes (dynamics). In the 28-year analysis we have been able to address this issue. The classes were generally similar to those in the 2002 analysis. However, class extinctions occurred over the 28 years and only four classes remained: three were stands of *Sporobolus* and the other was bare mud. The latter, with mangrove pneumatophores, represented the encroachment of *Avicennia* mangroves into salt marsh. We suggest that the class extinctions and the final loss of most of the plants represent a change in the processes operating in the marsh. The observed changes may be related to sea level and/or climate changes but future research would be needed to assess this.

**Abbreviation:** MML – Minimum Message Length.

> *No more things should be presumed to exist*
> *than are absolutely necessary.*
> Mark Haddon: The Curious Incident
> of the Dog in the Night-Time

## Introduction

This paper extends the analysis by Dale and Dale (2002) of a 14-year data set that explored the impacts of habitat modification for mosquito control on a south-east Queensland sub-tropical salt marsh using a Minimum Message Length (MML) approach. The modification was called runnelling and involved constructing shallow (< 0.30 m deep) and wide (0.90 m wide) runnels to connect tidal pools to the flooding source. This increased tidal flushing of the marsh, facilitated access of predatory fish and flushed mosquito larvae from the marsh on the ebb tide. Dale and Dale (2002) found no significant effect of the modification (runnelling). This conclusion has been supported by other research indicating that runnelling has had little impact on the salt marsh (Dale et al. 2002, Dale 2008, Dale and Knight 2012) so we have not further explored differences between the treatment and control here. We continue the research that Mike Dale was engaged in at the time of his death, when he was analysing 28 years of data from the same study area, again using the Minimal Message Length (MML) approach. We have applied the same methodology and research process here (for details of the process, see Figure 1 in Dale and Dale 2002).

Dale and Dale (2002) noted that changes from class to class could represent a single process within which some sites (samples) shift between states (classes) or it might be that the process itself changes, resulting in new states or the extinction of older ones. The analysis of 14 years of data, although providing clear evidence of state changes, did not provide evidence of a process change. With a further 14 years of data we can start to address this issue.

The original method reported in Dale and Dale (2002) modelled the salt marsh vegetation using the MML principle to cluster the samples (see Boulton and Wallace 1970, Wallace 2005, Dowe 2011). In the 2002 paper, Mike Dale wrote (p. 21):

> **“**MML can be regarded as implementing a form of Occam’s Razor, in which simplicity is balanced against complexity in explaining phenomena. The former is represented by the message length needed to encode the cluster descriptions, the latter by the likelihood of the data conditional on the model.”

The information length in MML is measured in ‘nits’. These are ‘natural bits’ and are explained in Wallace (2005). Other benefits of the approach are that it is statistically invariant (i.e., transforming the co-ordinates does not affect the answer (Visser et al. 2012) and is stable in the presence of

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* A paper dedicated to the memory of Professor Michael Bodley Dale (1936-2014).

noise (which is common in ecological data). It is also useful where model uncertainty is important (Dale and Dale 2004). These benefits make it an appropriate tool for the current ecological research. For a recent review of MML modeling, see Kasarapu and Allison (2015).

The aim here is to repeat the MML analysis using 28 years of data, leading to construction of a process model illustrating changes of state and potentially of process.

## Data and methods

### *Study area and data*

The study area is a 0.5 ha intertidal salt marsh on Coomera Island (S27° 51', E153° 33'), at the northern end of the Gold Coast, south-east Queensland, Australia. Vegetation is relatively simple and composed of Marine Couch (*Sporobolus virginicus* (L.) Kunth)) and Samphire (*Sarcocornia quinqueflora* (Bunge ex Ung.-Stern)). There is Grey Mangrove (*Avicennia marina* (Forsk)) along the tidal inlet that floods the marsh. Generally mangroves are encroaching onto saltmarsh in Eastern Australia and specifically in south-east Queensland and this is related to rainfall and land use changes (Eslami-Andergoli et al. 2009, 2010). In the study area, early research indicated that the encroachment was not related to the modification (Jones et al. 2004). The area has semidiurnal tides and a tidal range of around 2 m. The marsh floods each month and more often on tides that are at least 2.45 m Australian Height Datum (around 0.28 m above Mean High Water Spring tides).

Data were collected every three months for 20 years between November 1984 and November 2005, with additional data collected during November 2008 and 2013. Plant data were collected in 30, 10 cm ×10 cm quadrats recording size and density of the two species (*Sporobolus virginicus*, a grass and *Sarcocornia quinqueflora*, a succulent). These were used for the clustering process. As well, data were recorded each time for soil water content, soil water salinity and pH, water table depth and salinity. These were not used in the clustering. After 8 years, crab holes became apparent in the quadrats and after 9 years mangrove (*Avicennia marina*) pneumatophores appeared and so the data collection was modified to include these. For more detail on method, please refer to Dale et al. (1993).

### *Clustering*

The MML clustering used a freely available program (Vanilla Snob, authored by Chris Wallace, at: http://www.datamining.monash.edu.au/software/snob/). To check for comparability with the earlier results, we re-analysed the 14-year data set with the method as downloaded. There was no apparent difference between the resulting classes and those from the 2002 analysis. The 28 years of data were then analysed in the same way using the same four attributes – the size and density of the two plant species. The clusters with the minimal message length were selected for further processing.

### *Processing the cluster results*

The processing of the cluster results followed a similar pattern to that in Dale and Dale (2002). The clustering determined the 'best' classes. The classes were described and tabulated in terms of their plant characteristics. The presence of classes was plotted by month for all the data. Next, a transition matrix was calculated from the results for the whole data set. That is, the transitions between classes for all sample sites over the 28 years were enumerated. This was used to construct the process model 'picture' as was done in the 2002 paper, showing symbolically how each class changed over subsequent observations. It indicated relatively stable classes and those which changed from class to class over time. We used a cut off of 10% change from one class to another to show strong change and a 5% cut off for less frequent changes. Classes remaining in the same class from time to time were also noted.

### *Class associations with other attributes*

We further investigated associations between the classes from the MML analysis with those attributes that were not used to classify, noted above. We used an ANOVA with classes as the treatment. Where there were significant ANOVA results we did an extended t-test and means comparison to identify specific class relationships.

## Results

### *Clusters*

The MML procedure indicated that a 13-class cluster had the minimal message length. The 1-class length (all the data ignoring any pattern) was 73228.7 nits, whereas the 13-class length was only 42250.6 nits. The redundancy or structure captured is the difference between these numbers, in this case 30978.1. The greater the size of this difference the more likely it is that the clusters did not occur by chance. This represents an odds ratio in favour of the 13 cluster solution, compared to one cluster solution of $e^{30978.1}$: 1 or ~ 4 $\times 10^{13453}$: 1 which is a *very large* number. We therefore accept first, that clusters exist in these data and second, that 13 is a reasonable estimate of the number of such clusters.

### *Vegetation classes*

Table 1 shows the vegetation classes, number of samples in each class and the plant characteristics. The classes are similar to those reported in Dale and Dale (2002) with *Sporobolus* and *Sarcocornia* alone or in combination distinguished by their size, density and species combinations.

### *Distribution over time (28 years of data)*

Figure 1 illustrates the distribution of classes over time (by months from the start in 3-month steps). It shows that a

**Table 1**. Vegetation classes. Mean values for the plant attributes for each class (Sp – *Sporobolus*; Sa – *Sarcocornia*).

| Class ID | Class Description | # samples | Sp # /100cm$^2$ | Sp Height (mm) | Sa # /100cm$^2$ | Sa Size (mm) |
|---|---|---|---|---|---|---|
| 1 | Extremely tall, very dense *Sporobolus* | 215 | 182.14 | 128.77 | 0 | 0 |
| 2 | Very tall, medium dense *Sporobolus* | 566 | 90.20 | 101.23 | 0 | 0 |
| 3 | Very tall, medium dense *Sporobolus*; medium, sparse *Sarcocornia* | 57 | 89.79 | 102.45 | 7.19 | 50.19 |
| 4 | Tall, medium dense *Sporobolus*; short, medium dense *Sarcocornia* | 88 | 85.96 | 81.73 | 33.10 | 38.57 |
| 5 | Tall, sparse *Sporobolus*; very large, dense *Sarcocornia* | 33 | 38.76 | 86.26 | 60.42 | 126.19 |
| 6 | Tall, sparse *Sporobolus*; short, medium dense *Sarcocornia* | 175 | 23.39 | 87.08 | 33.45 | 38.25 |
| 7 | Tall, very sparse *Sporobolus* | 165 | 17.09 | 94.63 | 0.00 | 0.00 |
| 8 | Short. very sparse *Sporobolus*; medium, dense *Sarcocornia* | 62 | 10.02 | 43.74 | 74.00 | 57.97 |
| 9 | Medium, very sparse *Sporobolus;* short, medium dense *Sarcocornia* | 143 | 3.71 | 60.55 | 40.09 | 39.23 |
| 10 | Medium, very sparse *Sporobolus* | 161 | 3.28 | 71.55 | 0.00 | 0.00 |
| 11 | Large, very dense *Sarcocornia* | 31 | 0 | 0 | 92.32 | 75.83 |
| 12 | Short, medium dense *Sarcocornia* | 440 | 0 | 0 | 41.83 | 43.31 |
| 13 | Bare mud | 324 | 0 | 0 | 0 | 0 |

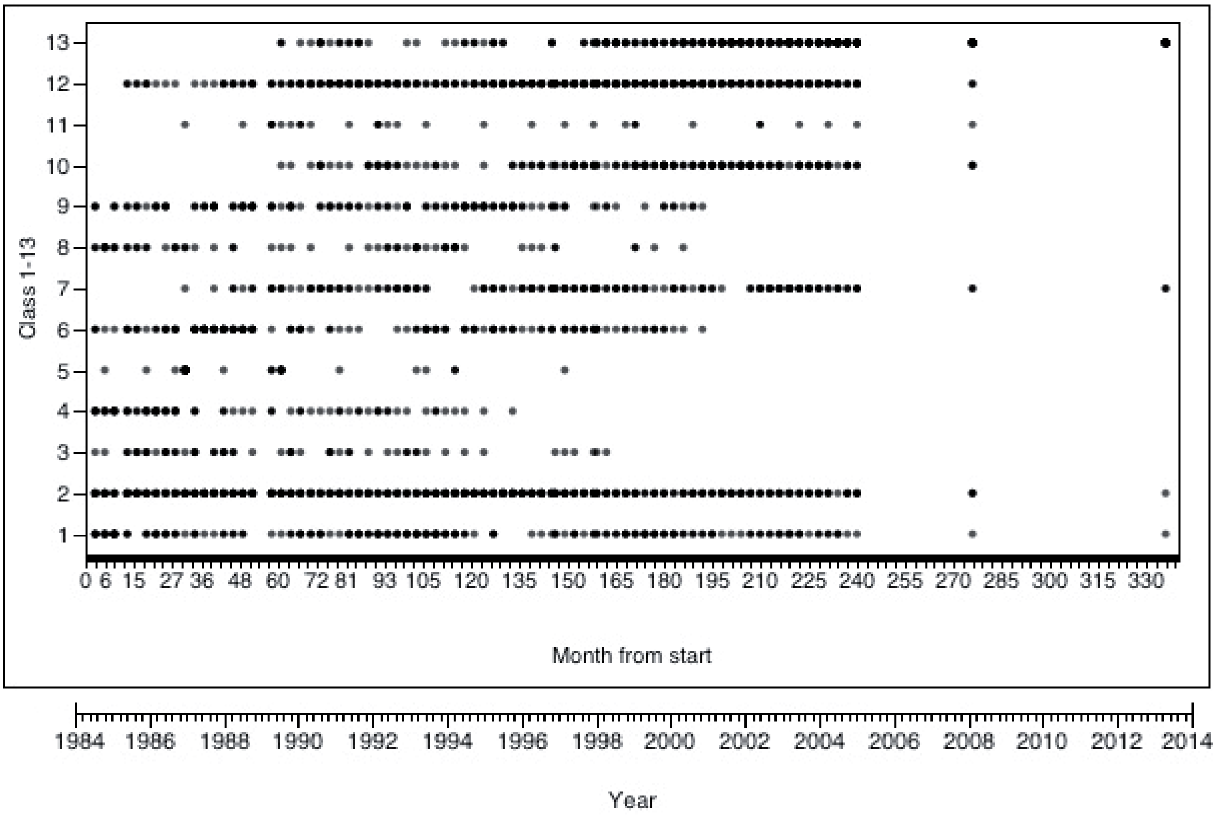

**Figure 1.** Classes every 3 months from 1985 to 2005 and 2008 and for 2013.

**Table 2.** Transition matrix for the whole data set .Diagonal values are lightly shaded and in italics (i.e., the situation when the class stayed the same from one tine to the next). Relatively stable classes (where there was no change, > 50% of the time – bold italics (median is 55% mean is 49%; upper 95% is 63%). Major change,10% of the time in bold; minor change, 5-10% of the time in italic.

| To<br>From | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | ***125*** | **85** | 2 |  |  |  | 2 |  |  |  |  |  |  | 214 |
| 2 | **81** | ***416*** | *14* | 6 | 1 | 5 | *34* |  |  | 1 |  | 1 | 6 | 565 |
| 3 | 2 | **14** | *18* | **15** | 1 | **7** |  |  |  |  |  |  |  | 57 |
| 4 |  | 3 | **12** | ***48*** | *7* | **16** |  | 1 |  |  |  | 1 |  | 88 |
| 5 |  |  | *3* | **6** | *4* | **15** |  | 1 | **4** |  |  |  |  | 33 |
| 6 |  | 5 | 7 | 6 | *14* | ***92*** | 7 | *11* | **26** | 2 | 2 | 3 |  | 175 |
| 7 | 1 | **26** |  |  | 1 | 2 | ***98*** |  | 1 | **24** |  | 1 | *9* | 163 |
| 8 |  |  |  |  | 1 | **16** |  | *21* | **21** |  | 1 | 2 |  | 62 |
| 9 |  |  |  | 1 | 3 | **18** | 1 | **19** | *59* | 2 | 1 | **35** | 4 | 143 |
| 10 |  |  |  |  |  | 1 | *16* |  | 3 | ***90*** | 1 |  | 50 | 161 |
| 11 |  |  |  |  |  |  | 1 | 1 | 1 |  | *2* | **24** | *2* | 31 |
| 12 |  | 3 |  |  | 1 |  | 2 | 6 | *24* |  | *22* | ***355*** | *27* | 440 |
| 13 |  | 5 |  |  |  |  | 4 |  | 1 | **42** | 2 | *18* | ***226*** | 298 |
| Total | 209 | 557 | 56 | 82 | 33 | 172 | 165 | 60 | 140 | 161 | 31 | 440 | 324 |  |

few classes persisted throughout the 28 years whereas others died out in the late 1990s (Classes 3, 4 and 5), and others that were not there at the start came into existence later e.g., Classes 10 and 13 in 1990 (very sparse *Sporobolus* and mud); Class 7 in 1987 (tall sparse *Sporobolus*) and class 5 (tall sparse *Sporobolus* and dense *Sarcocornia* in 1986.

### *Transition matrix*

The transition matrix is shown in Table 2. The first column is the starting class for any transition and the rows indicate the number of changes from the starting class to other classes (top row) or how many stayed the same (on the diagonal). The transition matrix will not be discussed in detail here as it was used to construct the process model and transitions are more clearly indicated in the model (Fig. 2).

### *The process model*

Figure 2 shows the process model illustrating the plant descriptions for each class with the processes identified from the transition matrix (Table 2). The model shows pathways of change from class to class, indicating, for example, reduction in plant size and density or recovery. This can be illustrated by the transitions between the *Sporobolus* classes on the left side of Figure 2. The changes from Classes 1 to 2 to 7 indicate reducing plant size and density. Changes from Classes 10 to 7 to 2 suggest recovery.

Some classes are relatively stable. The three most stable are classes 2, 12 and 13. Class 2 persists for the whole time period (with some Class 7 and Class 1). Classes 12 and 13 are large classes and represent increase in bare mud generally and the ultimate demise of the *Sarcocornia* component of the marsh (the last record of *Sarcocornia* in the field data was in 2008 when it was present in only three samples).

In more detail the process model shows two main pathways of change. The simplest is on the left representing *Sporobolus* classes whereby change is evidenced in the size and density of the plants. Between classes 1 and 2 there is a strong connection in both directions; other transitions appear to be asymmetrical. For example, the transition from Class 2 to Class 7 is relatively weak (6% of transitions from Class 2), with *Sporobolus* declining in size and density, whereas the reverse is a stronger transition (16% of transitions from Class 7 to Class 2).

On the right hand side of Figure 2 the transitions are more complicated with multiple links. The main link to the pure *Sporobolus* classes on the left is by a transition via Class 3 (or a by a very complex set of changes at the lower end of the figure). However, Class 3 also has strong links to Classes 4 and 6, each with increasing amounts of *Sarcocornia*. These classes link directly or indirectly to Class 9 with reduced plant size and density. Class 9 begins a sequence including Classes 12, 11 and 13, which latter represents bare mud and the loss of *Sarcocornia*. The *Sarcocornia* in Class 11, a relatively small class, appears to be tall and dense but its strong link is with Class 12, representing a decline in size and density. While recovery appears possible, for example the weak link from Class 12 (short medium dense *Sarcocornia*) to Class 11 (tall dense *Sarcocornia*), the reverse transitions are mainly weak ones.

Figure 3 illustrates the sequence of classes for two samples: one, Figure 3A, illustrates the *Sporobolus* sequence; the other, Figure 3B, shows an example of the *Sarcocornia* se-

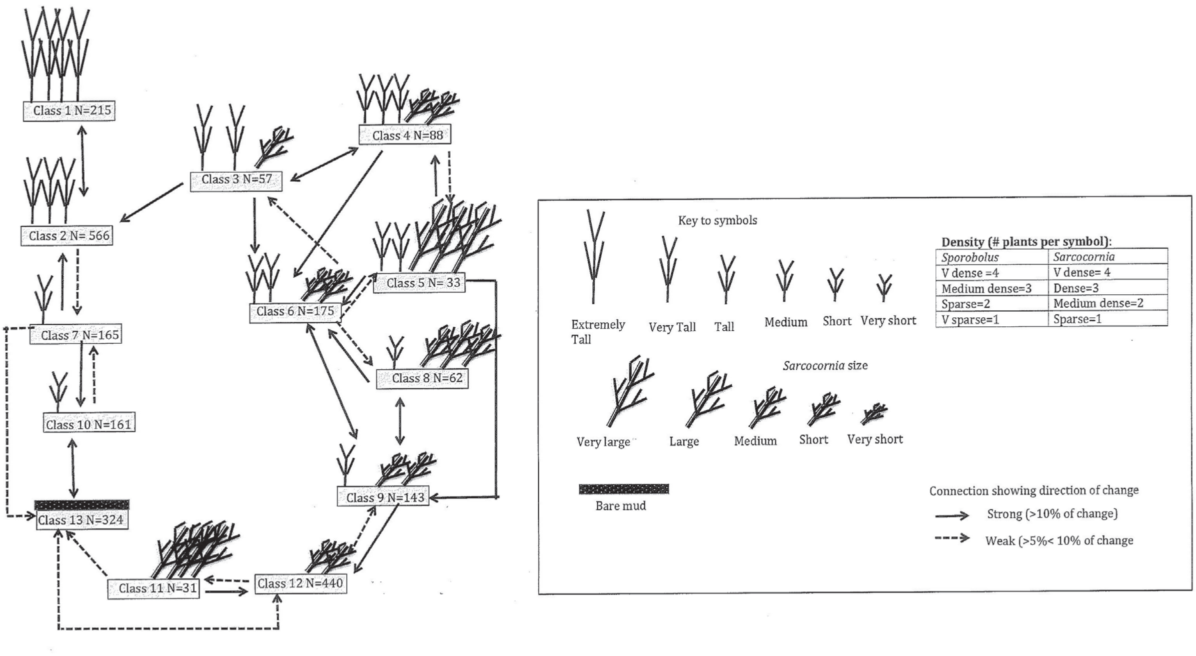

**Figure 2.** The process model.

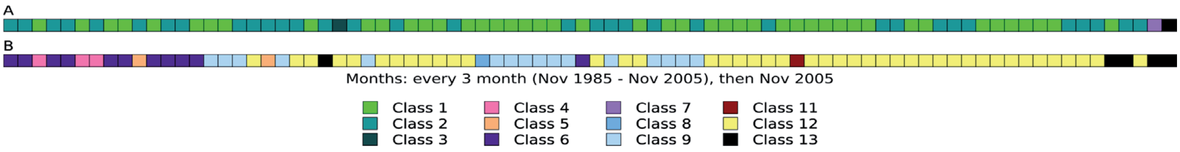

**Figure 3.** Examples of the processes for selected samples: **A.** *Sporobolus* transitions (left side of left panel in Fig. 2); **B**. Mixed spp. and *Sarcocornia* transitions (right side of left panel in Fig. 2).

quence that starts with the 4-5-6 circulation and finishes with the 9-13 extinction of the species.

The sequences are generally consistent with the process model in Figure 2 with very minor difference related to the 5% cut off for transitions that resulted in rare changes not being included in the model. For example, in Figure 3A Class 3 transitioned strongly to Class 2 once (as in the model) but, in the specific sequence illustrated, it also transitioned back from Class 2 to Class 3 (in 1992). This only occurred in 2% of the transitions from Class 2. In Figure 3B the transitions were more complex and Class 6 shows two direct transitions to Class 4 not in the model (this occurred in only 3% of transitions from Class 6 (n=6)). Similarly Class 12 transitioned to Class 5 (in 1990) but this only occurred once for the whole data matrix. Class 6 transitioned directly to Class 12 in 1996 (2% of transitions from class 6).

### *Class associations with other attributes*

There are relationships between some classes and the attributes that were not used in the classification (soil water content, soil salinity and pH; water table salinity; and pneumatophores and crab holes). This is shown in Table 3 and discussed below.

### *Soil water content and salinity*

Classes with *Sporobolus* and without *Sarcocornia* (Classes 1, 2, 7 and 10, ranging from tall dense to shorter less dense stands) were all associated with significantly higher soil water content and, except for Class 2, had significantly lower soil salinity. Class 7 (tall, very sparse *Sporobolus)* also had significantly lower water table salinity. Although not significant, the *Sporobolus* classes tended to be further from the tidal source (> 90 m except for Class 10).

Classes associated with significantly lower soil water content (Classes 5, 8 and 11) were mainly of large – medium dense *Sarcocornia* (with some sparse *Sporobolus* in classes 5 and 8). Classes 5 and 8 (and also class 4) were associated with high water table salinity. Classes 11 and 12 with only *Sarcocornia* were associated with lower soil water content and lower water table salinity (but not significantly so for Class 12).

In the process model there is a strong connection from class 11 (which remained the same for only 7% of transitions) to Class 12 and a high percentage of samples in Class 12 remained in that class (81%).

**Table 3.** Vegetation classes and significantly associated variables not used in the classification (P < 0.0001 ANOVA). Results here are based on means comparison in the t-test and rounded to 2 decimal places. Highest that are not significantly different from each other (bold); Lowest that are not significantly different from each other (italics).

| Class | Class description | Soil water (g/g) | Soil salinity (ppt) | Water table salinity (ppt) | Pneumatophores (n) | Crab holes (n) | Distance from tidal inlet (m) |
|---|---|---|---|---|---|---|---|
| 1 | Extremely tall, very dense *Sporobolus* | **0.61** | *34.77* | 30.52 | 0.00 | 0.30 | 91.33 |
| 2 | Very tall, medium dense *Sporobolus* | 0.61 | 36.35 | 29.62 | 0.03 | 0.23 | 90.80 |
| 3 | Very tall, medium dense *Sporobolus*; medium, sparse *Sarcocornia* | 0.59 | 39.69 | *28.33* | 0.00 | 0.04 | *74.65* |
| 4 | Tall, medium dense *Sporobolus*; short, medium dense *Sarcocornia* | 0.58 | 42.50 | **34.00** | 0.00 | 0.00 | 88.98 |
| 5 | Tall, sparse *Sporobolus*; very large, dense *Sarcocornia* | *0.58* | 38.92 | **33.65** | 0.00 | 0.06 | 89.09 |
| 6 | Tall, sparse *Sporobolus*; short, medium dense *Sarcocornia* | 0.59 | *33.65* | *27.22* | 0.09 | 0.07 | 93.03 |
| 7 | Tall, very sparse *Sporobolus* | 0.61 | *31.92* | *28.38* | 0.01 | 0.55 | 92.45 |
| 8 | Short, very sparse *Sporobolus*; medium, dense *Sarcocornia* | *0.54* | **49.45** | **35.79** | 0.08 | 0.10 | *75.81* |
| 9 | Medium, very sparse *Sporobolus;* short, medium dense *Sarcocornia* | 0.58 | 39.29 | 30.52 | 0.04 | 0.15 | 88.95 |
| 10 | Medium, very sparse *Sporobolus* | **0.61** | *33.21* | 31.22 | 0.03 | **0.84** | 84.75 |
| 11 | Large, very dense *Sarcocornia* | *0.56* | 37.23 | *29.21* | 0.06 | 0.19 | 91.94 |
| 12 | Short, medium dense *Sarcocornia* | 0.57 | 38.39 | 31.48 | 0.23 | 0.17 | 92.09 |
| 13 | Bare mud | 0.58 | 36.10 | *29.31* | **0.44** | **1.31** | *78.02* |

### *Pneumatophores and crab holes*

Classes 10 and 13 are characterised by mangrove pneumatophores and crab holes that appeared 8-9 years after the monitoring began. Class 10 had high soil water content and a significantly higher number of crab holes; Class 13 was bare mud and with significantly higher numbers both of pneumatophores and crab holes (and lower water table salinity). Linked to Class 13 were Classes 7-12, also with pneumatophores, and which were part of the process of loss of vegetation cover from relatively tall sparse *Sporobolus* to shorter *Sporobolus* (Class 10) to bare mud (Class 13) with some oscillation between the *Sarcocornia* classes (11 and 12).

## Discussion

The classes identified using 28 years of data are broadly similar to those identified in the 14 years analysis of Dale and Dale (2002). The tall dense *Sporobolus* is a distinct class in both, but with variation in terms of size and density in the 28-year analysis. The *Sarcocornia* and *Sarcocornia/ Sporobulus* classes are also outputs of both analyses with similar associations between classes and variables not used in the classification process. For example, the tall dense *Sporobolus* class (Class 1 in both the 14-year and 28-year analyses) was associated with a soil water content of 61% (relatively wet); at the other extreme bare ground (mud) (Class 11 in the 14 year analysis; Class 13 here) was associated with being closer to the tidal source (69 m and 78 m, respectively). That there was a three-year gap and then a five-year gap in the data after the end of the 20 year data collection in 2005 does not seem to have affected the results of the MML, as no new classes emerged at those later periods.

The 2002 paper noted that the results of the analysis did not allow distinction between changes of state (within a single process) or a change in the process itself. We suggest that the results from the additional years of data provide compelling evidence to indicate not only changes in state but also a change in process. The extinction of some classes (not evident in the 14 year analysis) might reflect a change in the underlying drivers of the system and indicate a process change. For example, Class 5 – the very 'unstable' class – became extinct in 1998 (see above and Fig. 1). Other extinctions included Class 4 in 1996; Class 3 in 1999; Classes 6, 8 and 9 in 2001. These were all part of the connected *Sarcocornia* Classes and it seems that once in that part of the process the samples were doomed to become bare mud. At the end of the period, after 28 years, there were only four remaining classes: Class 1, Class 2, Class 7 (all *Sporobolus*) and Class 13 (bare mud). Checking the field data shows that in the final year only four samples had any vegetation and this consisted of *Sporobolus*. The local extinction of some classes indicates that a tipping point may have been passed and this strongly supports a change in process. Using the same data in another context Eslami-Andergoli et al. (2015) showed that some indicators of tipping points were manifest at the Coomera site (e.g., increasing variance, increasing skewness).

The drivers underlying the process of change are not indicated by our analysis but the associations with other attributes suggest that water and its salinity are important (in the soil and water table). This in turn might indicate that some aspect of climate change related to rainfall or sea level is leading to significant alteration in marsh processes in this area. There is evidence that sea level in the general area is rising at a rate of around 3 mm/year (National Tidal Centre 2011), but what is not certain is how far marsh accretion will adjust for this. Rainfall can be very variable and was shown to be a driver of mangrove encroachment into salt marsh to the north of the study area (Eslami-Andergoli et al. 2009). Analysis of rainfall and sea level is beyond the scope of this paper but is worthy of further research.

## Conclusion

We have shown that the MML method has simplified the salt marsh system to provide a clear and simple exposition of the states or classes that exist or have existed within the salt marsh and an interpretable process model. The issue of change in state within a process or a change in the process itself has been addressed and we conclude that there is evidence that the underlying process has changed and that this may be related to local climate changes including rainfall and sea level. This would benefit from further research in the future.

Finally, as Mike Dale wrote in his last paper (Dale 2013), we include a quote from Isaac Newton:

> "Truth is ever to be found in the simplicity, and not in the multiplicity and confusion of things"

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