Coastal carbon opportunities: changes in the distribution of mangrove and saltmarsh across South Australia (1987 – 2015)

TECHNICAL REPORT

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Executive summary

Mangrove and saltmarsh ecosystems play a vital role in healthy, functioning coastal systems and have the capacity to sequester large amounts of carbon, both through uptake of atmospheric carbon dioxide during photosynthesis and by trapping organic materials from sea and land based inputs. Because of their ability to provide a range of ecosystem services, not least carbon capture and storage, there is a need to better understand the distribution of saltmarsh and mangrove throughout the state, as well as how this may be changing in response to human activities (e.g. coastal development, illegal dumping, changing land use) and challenging environmental conditions (e.g. pollution, coastal squeeze, invasive species and climate change).

As part of our Coastal Carbon Opportunities project, we aimed to assess spatial and temporal changes in the distribution of mangrove and saltmarsh vegetation throughout South Australia using historical and new imagery to look at changes in area coverage of these two coastal vegetation communities. The primary data set that we used to assess this was the South Australian Department for Environment and Water's (DEW) SA Land Cover dataset, which was released in 2018. The SA Land Cover dataset is a modelled output, based on classification of spectral information from the Landsat satellite remote sensed imagery. The dataset covers the period from 1987 to 2015 and is provided as six composite epochs (1987 – 1990, 1990 – 1995, 1995 – 2000, 2000 – 2005, 2005 – 2010, 2010 – 2015), so can be used to assess change through time.

Using the SA Land Cover dataset, we estimated area coverage of 164.2 km^2 for mangrove and 197.6 km^2 for tidally influenced saltmarshes in 2015. We found that there had been a net increase in the area of both saltmarsh and mangrove ecosystems between 1987 and 2015, with a greater increase in saltmarsh (16 km^2, or an approximately 9% increase since 1987) than mangrove (7.9 km^2 or a 5% increase since 1987). However, it should be noted that a broad scale loss of these coastal ecosystems is likely to have occurred prior to the commencement of the Landsat satellite data coverage in 1987 (particularly in urban, industrial and agricultural areas). Therefore, the relatively small increases in area coverage reported here for the period between 1987 – 2015 should be viewed with that in mind.

There are some uncertainties around how well saltmarsh and mangrove are identified in the model-classified SA Land Cover dataset. For this reason, we carried out an external evaluation based on assessing change in the distribution and area coverage of mangrove and saltmarsh using manual digitisation of aerial photographs in two areas where changes had previously been reported in the literature (Torrens Island and Middle Beach, both on the east coast of Gulf St Vincent, north of Adelaide). We compared the results of the aerial photo change analysis with those based on the SA Land Cover dataset and found the area coverage estimates from the SA Land Cover dataset were 5% higher for mangrove and 25% lower for saltmarsh for the period 1987-2015. We propose that the aerial photograph based assessment is likely to be more representative of changes at a scale that is relevant to local and regional authority management activities. However, the SA Land Cover dataset is the best available state-wide mapping product to use for baseline carbon stock assessment and for the identification of broad scale gains and losses in saltmarsh and mangrove ecosystems. We therefore suggest a multi scale approach, which involves further local-scale external validation of the SA Land Cover dataset's classification of saltmarsh and mangrove (e.g. for other sites across the state using alternative data sources and comparing patterns of change). We believe this is a practical way forward, especially when relating the area and changes in the distribution of these ecosystems to carbon stocks and accumulation, as the results will improve accuracy at state scale and be more robust at validated sites. If the SA Land Cover dataset is found to be consistently unreliable in the mapping of saltmarsh and mangrove (after further external validation), a dedicated mapping and modelling program for these difficult-to-classify coastal vegetation types may be the best way forward.

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1 Introduction

Mangrove and saltmarsh habitats are distributed widely along the South Australian coastline and while they are vitally important to the functioning of coastal ecosystems, they have historically undergone significant declines in area coverage across the state (Edyvane 1999, Fotheringham and Coleman 2008, Harbison 2008, Harty 2004). Large, human induced, disturbance and clearance events have impacted saltmarsh and mangrove in South Australia from the arrival of European settlers, up until the early 1970s when they were first protected under the South Australian *Fisheries Act* (1971 and 1982), with further protections introduced decades later under the South Australian *Native Vegetation Act* (1991) and the Australian *Environmental Protection and Biodiversity Conservation Act* (1999; temperate saltmarshes only). Since their protection, the extent of mangrove and saltmarsh loss due to clearance, land-use change and development has reduced; however, they are still affected by pollution, illegal dumping and indirect human impacts such as climate change and sea-level rise (Saintilan and Williams 1999). The major cause of loss in mangrove and saltmarsh habitat observed today is “coastal squeeze” (Pontee 2013). This occurs when sea level rise and sedimentation results in mangroves retreating landward, which then infringes on saltmarsh habitat. Saltmarsh ecosystems would typically also extend their range landward in response to this, however, hard surfacing and human development along the coast now prevents this in many areas. In order to manage deterioration of mangrove and saltmarsh ecosystems in South Australia, we need to document their changing distribution. By doing so, we can better understand the sensitivity of these coastal vegetation communities to change, which can then be used to forecast responses to future climate conditions and adapt management strategies appropriately (Schimel et al. 2013).

It is important to monitor vegetation dynamics and gradual distribution changes as saltmarshes and mangroves provide a wealth of ecosystem services, including habitat for marine life and birds, coastline stability and protection, and they are a key element of the coastal food chain (Barbier et al. 2011). In addition, mangrove and saltmarsh ecosystems are extremely efficient at capturing and storing carbon, with global averages indicating that they have far greater storage potential than terrestrial forests (Mcleod et al. 2011). All of the ecosystem services provided by mangroves and saltmarshes have associated economic, societal and biodiversity benefits (Costanza et al. 2014).

The aims of this project were to:

- Assess spatio-temporal change in mangrove and saltmarsh communities in South Australia, using the Department of Environment and Water’s (DEW) SA Land Cover dataset (Willoughby et al. 2018), to look at changes in areal coverage of these two coastal vegetation communities over time.
- Assess key drivers of any changes, to improve our understanding of past changes in distribution of mangrove and saltmarsh ecosystems.
- Undertake an external evaluation of the SA Land Cover dataset’s ability to accurately detect tidally influenced saltmarsh and mangrove ecosystems.

To achieved these aims, and at the request of our collaborators in state government, we used the SA Land Cover dataset to assess change in the area coverage of tidally influenced mangrove and saltmarsh ecosystems across the state for the period from 1987 – 2015 (the temporal coverage of the SA Land Cover data layers and the underlying Landsat dataset).

Mangrove and saltmarsh can be difficult to distinguish using remote sensed Landsat data when mangrove canopy is sparse and underlying saltmarsh vegetation influences spectral signature (Rogers et al. 2018). The spectral characteristics of tidally influenced saltmarsh communities are also extremely similar to other vegetation communities such as stranded saltmarshes, arid-land halophytic woody vegetation and other low woody shrubs. This similarity can lead to commission errors in classification models and subsequent overestimation of the area coverage of tidal marshes. Such difficulties distinguishing between different vegetation and land cover classes can lead to inconsistent attribution of an area into one or other class, and is associated with uncertainty around trends when looking at change through time (Christman et al. 2015). These misclassifications and uncertainties are a well-documented, but as-yet unsolved issues and are not limited only to Landsat derived mapping products (Friess and Webb 2011, Friess and Webb 2014, Mejía-

Rentería et al. 2018). Due to these known issues, we took steps to reduce the influence of commission errors by cropping the dataset to the coastline (details in the methods section) as well as carrying out an external validation exercise using aerial photographs provided by DEW. The external validation was not part of the initial scope of the task, however, it was deemed necessary based on early analyses of the SA Land Cover dataset and discussion with staff from the DEW Environmental Information Unit.

2 Methods

2.1 SA Land Cover: background on the dataset

The South Australian Land Cover dataset is a modelled spatial data product covering the whole of South Australia with a resolution of ~ 25 x 25 m. Each grid cell is classified as one of 17 land cover classes during each of six 'epochs', or time steps covering the period 1987 to 2015 (Willoughby et al. 2018): 1987-1990, 1990-1995, 1995-2000, 2000-2005, 2005-2010 and 2010-2015. This dataset was generated using statistical model ensembles to classify Landsat data into specific land cover classes (White and Griffioen 2016). The SA Land Cover dataset is available as two main data products that describe the vegetation and land cover at each location across the state during each time period:

- The continuous layers: Two continuous layers are available for each specific land cover class (n = 17) per epoch. These layers represent the likelihood (probability) that a given cell contains a specified land cover class and the confidence (or variance) associated with the likelihood score.
    - The likelihood layer: a continuous layer where each grid cell has a probability score (0-100) of being a particular land cover class.
    - The confidence (or variance) layer: a continuous layer where each grid cell has a variance score (0-100) which represents the variance in the associated likelihood score for that cell with higher values representing lower confidence (greater variance).
- The most likely layer: each grid cell is categorised as a specific land cover class (n = 17) based on the modelled probabilities and associated variances in the continuous layers. There is a single most-likely layer for each epoch, which represents the most-likely land cover class in each grid cell for the given time period. A more detailed explanation on how the most likely layers were generated can be found in Willoughby et al. (2018).

The modelling process used to generate the SA Land Cover dataset is described in detail in White and Griffioen (2016) and Willoughby et al. (2018), but we provide a brief outline of the approach and model evaluation below, for context. The model ensemble used for land cover classification was calibrated and validated using exemplars, which are time-stamped point locations of specified land cover types collated from various existing projects and datasets. There were a total of 7442 mangrove and 1855 saltmarsh exemplar points (White and Griffioen 2016). These data were split 9:1 with 90% used to fit the model and 10% held back and used for model evaluation. The model's performance was assessed using the Kappa statistic, with the results for overall classification performance (across all 17 classes) suggesting that the most likely layers are, on average, between 88% and 92% better than might have been obtained by chance (Willoughby et al. 2018). However, the model performance was poorer for some land cover classes than others, with saltmarsh being one of the worst classifications achieved (Table 1, adapted from White and Griffioen, 2016). This result is representative of significant errors of omission and commission for the saltmarsh land cover class and is likely due to a) spectral similarity between the saltmarsh class and other similar vegetation classes (e.g. natural low cover, non-woody native) and b) relatively smaller number of exemplar points used for evaluating the SA Land Cover model's performance (mangrove = 744 and saltmarsh = 185). Some post-processing rectification was done by the developers to correct errors in model classification, for example when woody native vegetation was incorrectly classified as mangrove in areas more than 300 km inland, along the River Murray.

Table 1. SA Land Cover most-likely model classification evaluation statistics for the mangrove and saltmarsh classes (a higher number represents more accurate classification). Model evaluation statistics were taken from White and Griffioen (2016).

	COEFFICIENT OF DETERMINATION					
LAND COVER CLASS	1987-1990	1990 – 1995	1995 – 2000	2000 – 2005	2005 - 2010	2010 - 2015
Mangrove	0.906	0.920	0.905	0.918	0.924	0.903
Saltmarsh	0.676	N/A	0.512	0.668	N/A	0.276

2.2 SA Land Cover: dataset processing and summary statistics

After significant investigation into potential ways to use the SA Land Cover continuous data layers (the likelihood and probability layers) for this study, we found that the only feasible way to progress with this task was to use the most-likely data layers for saltmarsh and mangrove, despite an understanding of the caveats around the saltmarsh classification mentioned above (and see model evaluation statistics in Table 1).

The most likely SA Land Cover data layer was clipped to a coastal buffer of 5 km from the mean high-water mark, to eliminate incorrect classifications of mangrove and saltmarsh further inland. We appreciate that this coastal cropping will exclude some stranded saltmarshes, as well as saltmarshes that are in high salinity arid areas further inland (but not under the influence of tides). However, we made the decision to exclude these areas as our focus is blue carbon ecosystems, which are systems under the influence of tidal dynamics. The carbon sequestration potential of stranded and arid saltmarshes is likely to be very different from that of tidally influenced saltmarshes, and the former are certainly not considered under current definitions of blue carbon (Lovelock and Duarte 2019).

Having made the decision to crop at 5 km from the coastline, we carried out a visual evaluation of the cropped SA Land Cover dataset against DEW's Coastal Saltmarsh and Mangrove Mapping dataset, which is based on digitised aerial photos and dates back to 1997 (DEW dataset number 886; metadata download available from the SA Government Location SA metadata system at: http://location.sa.gov.au/lms/Reports/ReportMetadata.aspx?p_no=886&pa=dewnr). We found that by cropping the SA Land Cover dataset to 5 km from the coast, we did exclude some areas that were classified as 'intertidal saltmarsh' in the DEW Coastal Saltmarsh and Mangrove dataset (for an example area, see Figure 1, A). On further inspection however, we discovered that many of these excluded areas were not classified as saltmarsh in the full extent SA Land Cover dataset (Figure 1, B). The most common vegetation classes attributed to these discrepancy areas in the SA Land Cover dataset were natural low cover; salt lake / saltpan; non-woody native vegetation; and woody native vegetation. This demonstrates that there is clearly a difference in the classification of coastal vegetated areas between the earlier DEW mapping product (based on digitised aerial photos from across the state) and the SA Land Cover dataset. Nevertheless, we did find that our choice to crop our analysis area to within 5-km of the coastline resulted in differences in the estimates of the area of saltmarsh and mangrove compared (focussing on tidally influence ecosystems for the purposes of blue carbon) compared to that previously reported by DEW based on the SA Land Cover data (Willoughby et al. 2018; further details in the results section).

After cropping the SA Land Cover most-likely layer, we then converted it into two binary rasters for each epoch; one for saltmarsh and one for mangrove, where cells with a value on 1 indicated presence of the stated vegetation type and all other cells were given a value of 0. These layers were then multiplied by a scaled area grid layer (supplied by DEW) to ensure area estimates were accurate. This generated a single raster for each epoch, for each of the two vegetation classes, where each grid cell that was classified as mangrove or saltmarsh had a cell value that represented the area of that grid cell (and all other cells had a value of 0). This enabled easy comparison of change over time of the presence of each vegetation type at each location, as well as calculation of total area coverage for saltmarsh and mangrove in each epoch by summing across each raster layer.

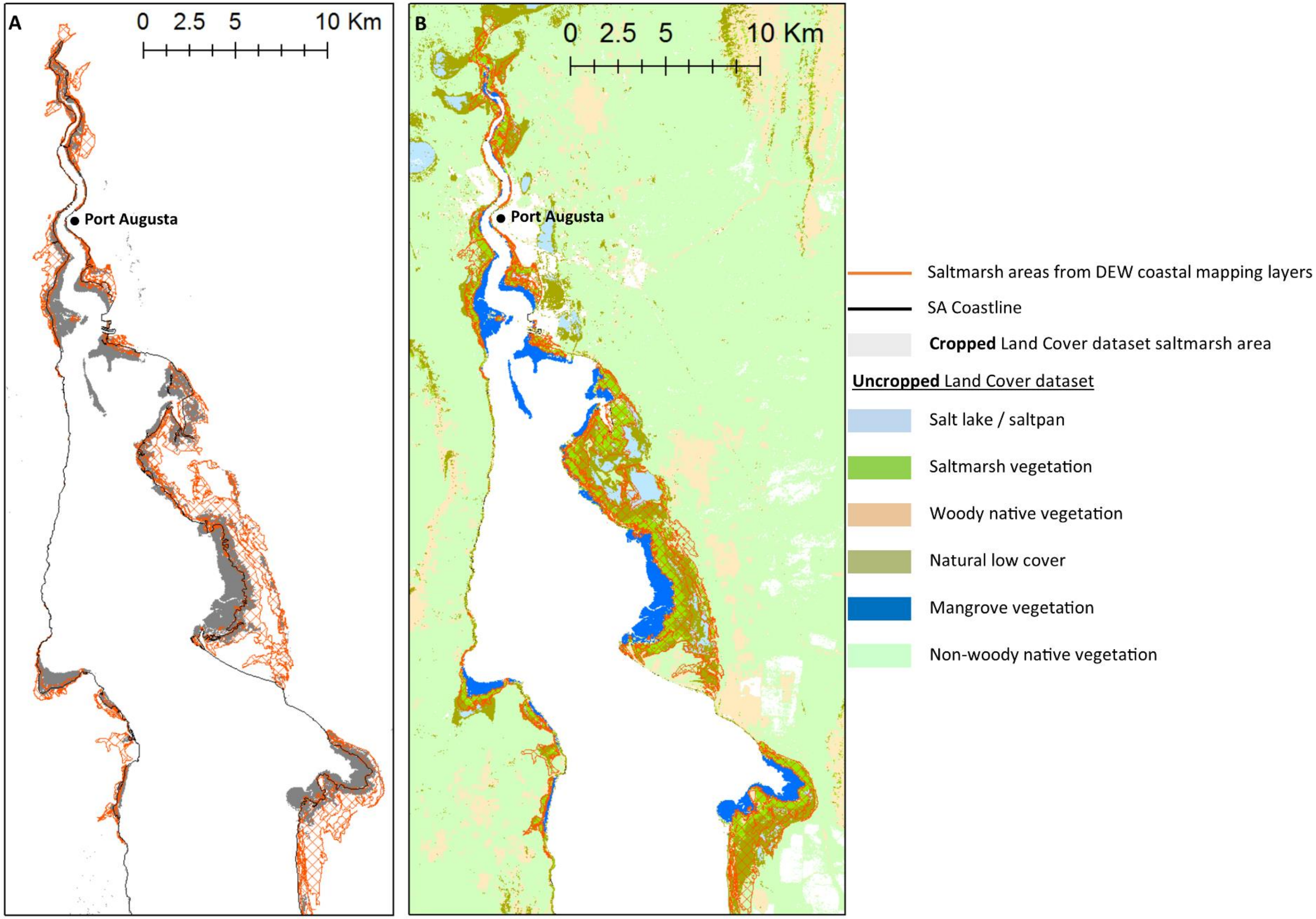

Figure 1. Comparison of vegetation classification in A) DEW coastal mapping saltmarsh and mangrove layer (1997) and the SA Land Cover dataset (most likely layer) cropped to 5 km from the coast and B) the DEW saltmarsh and mangrove mapping layer (1997) and the full extent (uncropped) Land Cover dataset (most likely layer).

2.3 Aerial photography

We obtained aerial photographs from DEW that ranged from 1949-2017 and covered areas throughout the State, but with best temporal replication (i.e. photographs from multiple years) along the eastern coast of Gulf St. Vincent around Adelaide. We then conducted a literature review to collate records where saltmarsh and mangrove change had been reported in the state over time. Change in both mangrove and saltmarsh had been reported at both Torrens Island and from Port Gawler to Middle Beach (hereafter referred to as Middle Beach) (Coleman et al. 2017). These two sites were chosen to externally validate the effectiveness of the Land Cover most likely layer to detect relatively fine scale change in these two coastal vegetation types. Using manually digitised and visually classified image data as a baseline against which to compare modelled land cover classifications is a commonly used approach (Cleve et al. 2008, Comber et al. 2004, Schwert et al. 2013). Visual assignment of vegetation type and land cover class by a human operator is generally acknowledged to be superior to automated classification in terms of accuracy, particularly for complex vegetation communities (Cleve et al. 2008, Comber et al. 2004, Husson et al. 2016) although has the drawback of requiring far more time and resources (which makes it unrealistic for high resolution assessments over large areas) (Alvarez et al. 2003, Husson et al. 2016).

It was found that the temporal coverage of the historical aerial imagery of the two validation sites do not match exactly, nor do they exactly match the epochs of the Land Cover dataset. For the Torrens Island site, the photos available were 1986-1989, 2006 and 2015 and for the Middle Beach site were 1986-1989, 2005 and 2015 (see Table 2). Given there is only one-year difference in the time periods of the two photos and the Land Cover epochs, we do not believe this impacted the results in a significant way.

All external validation work was undertaken in ArcGIS version 10.5.1. Initially, a polygon shapefile was created to outline the areas of interest (AOI; Torrens Island and Middle Beach). The aerial photograph files and the Land Cover raster layers were cropped to these AOIs. We then used heads-up manual digitising of a polyline feature to trace different land cover features within the areas of interest at a constant scale of 1:3000 (recommended by DEW). The polylines were then converted to polygons and the attribute table of the feature layer was edited to classify each individual feature into one of eight land cover classes based on visual assessment of the vegetation type present in the photograph using guidance from a saltmarsh and mangrove mapping data user guide provided by DEW (DEH 2007). There was no ground-truthing of these visual classifications (e.g. with field visits or other data sources), which would not have been possible for the older aerial images. The class of each polygon was attributed solely on the basis of the analyst's interpretation of the aerial photos and therefore there is some risk of manual misclassification. However, it should be noted that manual classification has previously been shown to be more accurate than automated classification (Comber et al. 2004, Husson et al. 2016). The 8 land cover classes were as follows: mangrove, saltmarsh, saltpan, algae, urban (defined as building or roads), bare, water and unsure. The classified shapefiles were then converted to rasters with the same extent and cell size as the SA Land Cover raster, so as to enable direct comparison. When generating the rasters from the digitised aerial photos, we used the 'maximum combined area' method, which identifies the dominant feature within each grid cell. Once the classified rasters had been generated for each time period, they were converted to binary rasters (presence-absence) for mangrove and saltmarsh at each time point. This processing was done in R (R core team 2018), using packages 'rgdal', 'raster', 'sp' and 'rastervis' (Bivand et al. 2018, Hijans 2019, Lamigueiro and Hijmans 2018, Pebesma and Bivan 2005) and resulted in a set of presence-absence rasters for each vegetation class, each year and each AOI (12 rasters in total) based on the aerial photographs. These could then be compared to the binary rasters generated from the Land Cover dataset.

Table 2. Temporal coverage of the different spatial data layers used for the two external validation areas.

SITE	MOST-LIKELY LAYERS	AERIAL PHOTOGRAPHY
Torrens Island	1987-2005	1986-2006
	2005-2015	2006-2015
	1987-2015	1986-2015
Middle Beach	1987-2005	1986-2005
	2005-2015	2005-2015
	1987-2015	1986-2015

2.4 Comparison between SA Land Cover (most likely) dataset and digitised aerial photographs

The following analyses were conducted in R (R Core Team 2017). We made direct comparisons between the binary (presence-absence) classification at each grid cell in the SA Land Cover (most likely) rasters and the aerial photography rasters for both vegetation classes and both AOIs at each time period. A function was created in R to compare change from one time period to the next in each of the datasets (photos vs Land Cover) separately. Change was classified using 4 categories:

- Present – no change: cell class indicated presence at both adjacent time periods (e.g. mangrove was present in both time periods).
- Absent – no change: cell class indicated absence at both adjacent time periods (e.g. saltmarsh was absent in both time periods).
- Gain – cell class changed from absent to present between adjacent time periods.
- Loss – cell class changed from present to absent between adjacent time periods.

Area of presence and areal gain/loss values were then calculated for each vegetation class at each time period from both the aerial photography rasters and the Land Cover rasters for comparison. The area represented by the grid cells changes with latitude and was corrected using the spatial area raster provided by DEW for this purpose. The grid cells within the Torrens Island AOI were all 632 m^2 and the grid cells within the Middle Beach AOI were all 633 m^2. Area values in square meters were converted to square km by diving by 1,000,000.

3 Results

3.1 State-wide results from the SA Land Cover (most likely) dataset

We cropped the SA Land Cover dataset using a buffer of 5 km from the high water mark (see discussion and justification of this decision in the methods, section 2.2). This led to differences in area estimates of saltmarsh and mangrove reported here, compared to those reported in Willoughby et al. (2018), which are based on the same dataset but not cropped to the coastline. Both vegetation classes were estimated to cover a larger area in Willoughby et al. (2018), with a relatively small difference for mangrove, but a large difference for saltmarsh (Table 3).

Table 3. Area coverage estimates for 2010 – 2015 from Willoughby et al. 2018 and our analysis which used the cropped dataset.

ECOSYSTEM	COVER ESTIMATE FROM WILLOUGHBY ET AL. (2018) (KM^2; NOT CROPPED)	COVER ESTIMATE FROM THIS STUDY (KM^2; CROPPED TO 5KM FROM COAST)
Mangrove	170	164
Saltmarsh	350	198

Using the cropped Landsat-derived modelled SA Land Cover dataset to assess state-wide change in the coverage of saltmarsh and mangrove indicates a net increase in both types of vegetation over the period from 1987 to 2015 (Table 4). The increase was consistent through time for mangrove, although a small decrease between the last two epochs was observed. Saltmarsh coverage was more variable through time, with an overall increase for the full time period but a decrease from 2005 onwards (Table 4, Figure 2).

Table 4. Summary data on area coverage of saltmarsh and mangrove in South Australia through time, from the SA Land Cover (most likely) dataset.

EPOCH	MANGROVE AREA (KM^2)	SALTMARSH AREA (KM^2)
1987-1990	156.3	181.6
1990 - 1995	160.9	197.8
1995 - 2000	162.0	198.1
2000 - 2005	163.8	199.7
2005 - 2010	164.9	194.7
2010 - 2015	164.2	197.6

Although there was a slight net increase in both ecosystems between 1987 and 2015, there were areas of gain and loss in each epoch, indicating a shift in the distribution of mangrove and saltmarsh (Table 5 and Table 6). This shift was particularly apparent for saltmarsh with larger areas of both gain and loss between epochs than were recorded for mangroves (Table 5). This may be indicative of a dynamic system that is constantly moving through a series of die-back and colonisation events. Alternatively, it may represent variability in the model's ability to correctly classify the saltmarsh, leading to grid cells moving in and out of this land cover class more readily. There are no data that capture uncertainty around the most likely layer classification in the SA Land Cover product, therefore it is difficult to know how much we can rely on these results, particularly because the changes in areal coverage of the two vegetation classes are relatively small and variable, meaning that they may fall within the classification error of the modelled data layers.

Table 5. Detailed assessment of gain and loss through time in area of mangrove in South Australia based on coastally cropped SA Land Cover dataset.

CHANGE PERIOD	MANGROVE AREA (KM^2)	MANGROVE GAIN (KM^2)	MANGROVE LOSS (KM^2)	MANGROVE NET CHANGE (KM^2)
1990 - 1995	160.9	7.5	2.9	4.6
1995 - 2000	162.0	4.7	3.5	1.1
2000 - 2005	163.8	5.0	3.2	1.8
2005 - 2010	164.9	3.8	2.7	1.1
2010 - 2015	164.2	4.7	5.5	-0.7

Table 6. Detailed assessment of gain and loss through time in area of saltmarsh in South Australia based on coastally cropped SA Land Cover dataset.

CHANGE PERIOD	SALTMARSH AREA (KM^2)	SALTMARSH GAIN (KM^2)	SALTMARSH LOSS (KM^2)	SALTMARSH NET CHANGE (KM^2)
1990 - 1995	197.8	33.2	17.0	16.2
1995 - 2000	198.1	22.1	21.8	0.3
2000 - 2005	199.7	22.6	20.9	1.6
2005 - 2010	194.2	16.1	21.6	-5.56
2010 - 2015	197.6	30.5	27.1	3.44

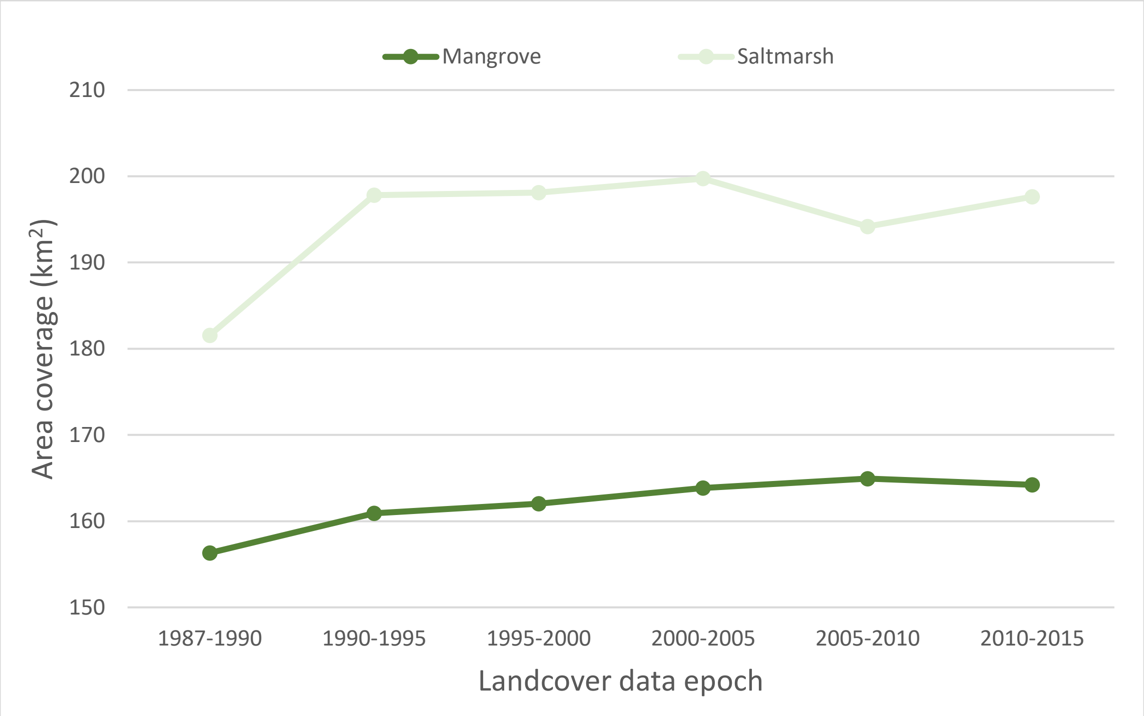

Figure 2. Area coverage through time for saltmarsh and mangrove in South Australia based on the DEW SA Land Cover most likely dataset (cropped to the coast using a 5 km buffer).

3.2 Results of the site-based external validation of the trends in the SA Land Cover dataset using digitised aerial photographs

Torrens Island validation area

The SA Land Cover most likely dataset estimates of mangrove and saltmarsh vegetation extent differed to those from the digitised aerial photography within the Torrens Island area of interest (see maps in Appendix), with a greater discrepancy observed in the saltmarsh estimates (Table 7 and Table 8). The estimates of area coverage from the SA Land Cover (most likely) dataset tended to be higher mangrove and lower for saltmarsh than the area estimates from the aerial photos (Table 7 and Table 8).

It appears that the digitised aerial photographs were more accurate at capturing change in the coverage of the saltmarsh and mangrove within the AOIs than the Land Cover data (Figure 3). Analysis of the SA Land

Cover most likely raster classifications revealed that this modelled data product (based on Landsat data) appeared to be incorrectly classifying bare ground as the nearest vegetation type, which was either mangrove or saltmarsh. This explains why there was no change observed in the most likely layers and a gain in the aerial photographs. The lack of detection by the most likely layer could be due to the inability to classify change at this fine scale. However, it should also be noted that the land cover class attributed to the manually digitised aerial images was done based on visual assessment of the photographs. This is a standard approach and visual classification has been shown to be more accurate than a computer-based approach to land cover classification (Christman et al. 2015, Comber et al. 2004, Husson et al. 2016). Assuming (on the basis of the assessment shown in Figure 3) that the classification of the aerial imagery is more accurate than the classification of the SA Land Cover dataset; we calculated absolute difference in area change estimates between the two different assessment methods (for the period 1987 - 2015). The results are given in Table 9 and suggest that the SA Land Cover dataset generally overestimated change for mangrove and underestimated change for saltmarsh in the Torrens Island area.

Table 7. Comparison of estimates of mangrove cover and change in area over time between the SA Land Cover most likely layers and digitised aerial photography for the Torrens Island validation area of interest. Shading has been used to highlight the time periods that are comparable using the different data layers.

DATA	CHANGE PERIOD	PRESENCE (KM^2)	RETAINED (KM^2)	GAIN (KM^2)	LOSS (KM^2)	NET CHANGE (KM^2)
Most likely layer	1987-2005	13.7	13.4	0.4	0.9	0.5
	2005-2015	13.6	13.4	0.1	0.3	0.5
	1987-2015	13.6	13.2	0.4	0.4	0.9
Aerial photography	1986/89-2006	13.1	11.9	1.2	0.2	0.9
	2006-2015	12.9	12.6	0.3	0.5	-0.2
	1986-2015	12.9	11.8	1.1	0.4	0.7

Table 8. Comparison of estimates of saltmarsh cover and change in area over time between the SA Land Cover most likely layers and digitised aerial photography for the Torrens Island validation area of interest. Shading has been used to highlight the time periods that are comparable using the different data layers.

DATA	CHANGE PERIOD	PRESENCE (KM^2)	RETAINED (KM^2)	GAIN (KM^2)	LOSS (KM^2)	NET CHANGE (KM^2)
Most likely layer	1987-2005	2.8	2.4	0.4	0.3	0.7
	2005-2015	2.8	2.6	0.2	0.3	0.6
	1987-2015	2.8	2.3	0.6	0.4	1.0
Aerial photography	1986/89-2006	3.4	2.6	0.8	1.2	-0.4
	2006-2015	3.4	2.7	0.7	0.7	0.0
	1986-2015	3.5	2.3	1.1	1.5	-0.4

Table 9. The absolute difference between 'presence' estimates for mangrove and saltmarsh from the SA Land Cover most likely layers and the aerial photography data at the Torrens Island validation area of interest.

VEGETATION	CHANGE PERIOD	ABSOLUTE DIFFERENCE
Mangrove	1986/1989-2005/6	0.6 km^2
	2005/6-2015	0.7 km^2
	1986/7-2015	0.7 km^2
Saltmarsh	1986/1989-2005/6	-0.6 km^2
	2005/6-2015	-0.6 km^2
	1986/7-2015	-0.7 km^2

+ = likely over estimated in the SA Land Cover dataset; - = likely underestimated in the SA Land Cover dataset

Middle Beach validation area

Comparisons between the SA Land Cover most likely dataset and the aerial photography change estimates reveal a large discrepancy in both mangrove and saltmarsh change through time (see maps in Appendix). Where the SA Land Cover dataset shows a loss of mangrove vegetation from 1987 to 2015, the aerial photography shows a gain (Table 10). For saltmarsh vegetation, the SA Land Cover dataset indicate a small gain in area coverage, but the aerial photography suggests a much larger gain (Table 11)**.** The absolute difference estimates for overall change in area of saltmarsh and mangrove (1987 – 2015) according to the two different methods of assessment, show the SA Land Cover dataset underestimated change for both mangrove and saltmarsh in the Middle Beach area (Table 12). This is illustrated in

Figure 4, which shows a clear landward progression of both mangrove and saltmarsh vegetation in the aerial photograph that was not detected by the SA Land Cover most likely layers. Instead, these areas were classified in either the 'woody native' or 'wetland vegetation' land cover classes, indicating errors of omission in the SA Land Cover most likely layers in this case.

Table 10. Comparison of estimates of mangrove cover and change in area over time between the SA Land Cover most likely layers and digitised aerial photography for the Middle Beach validation area of interest. Shading has been used to highlight the time periods that are comparable using the different data layers.

	CHANGE PERIOD	PRESENCE (KM^2)	RETAINED (KM^2)	GAIN (KM^2)	LOSS (KM^2)	NET CHANGE (KM^2)
Most Likely layer	1987-2005	10.0	9.4	0.5	0.3	0.2
	2005-2015	10.0	9.2	0.3	0.9	-0.5
	1987-2015	10.0	8.8	0.7	0.9	-0.2
Aerial photography	1986/89-2005	10.2	7.8	2.3	0.5	1.8
	2005-2015	10.9	9.7	1.2	0.5	0.7
	1986-2015	10.9	7.9	3.0	0.5	2.6

Table 11. Comparison of estimates of saltmarsh cover and change in area over time between the SA Land Cover most likely layers and digitised aerial photography for the Middle Beach validation area of interest. Shading has been used to highlight the time periods that are comparable using the different data layers.

DATA	CHANGE PERIOD	PRESENCE (KM^2)	RETAINED (KM^2)	GAIN (KM^2)	LOSS (KM^2)	NET CHANGE (KM^2)
Most likely layer	1987-2005	4.6	3.8	0.8	0.5	0.4
	2005-2015	4.4	4.0	0.5	0.7	-0.3
	1987-2015	4.4	3.5	0.9	0.8	0.1
Aerial photography	1986/89-2005	3.8	2.7	1.1	2.0	-0.8
	2005-2015	6.6	2.9	3.7	0.9	2.8
	1986-2015	6.7	3.0	3.6	1.6	2.0

Table 12. The absolute difference between 'presence' estimates for saltmarsh and mangrove from the SA Land Cover most likely layers and the aerial photography data at the Middle Beach validation area of interest.

VEGETATION	CHANGE PERIOD	ABSOLUTE DIFFERENCE
Mangrove	1986/1989-2005/6	-0.2 km^2
	2005/6-2015	-0.9km^2
	1986/7-2015	-0.9 km^2
Saltmarsh	1986/1989-2005/6	0.8 km^2
	2005/6-2015	-2.2 km^2
	1986/7-2015	-2.3 km^2

+ = likely over estimated in the SA Land Cover dataset; - = likely underestimated in the SA Land Cover dataset

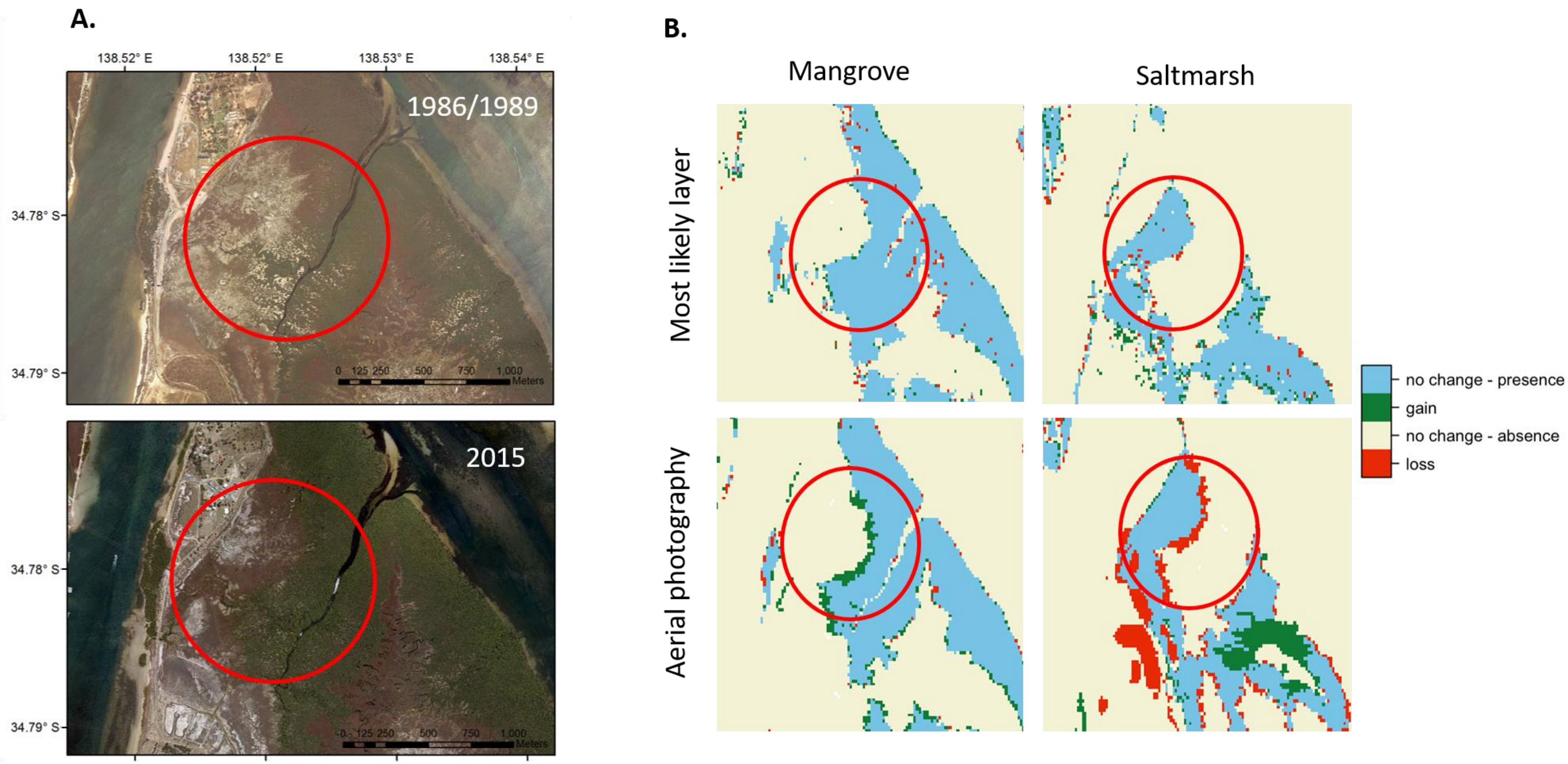

Figure 3. A) Aerial photography showing changes in mangrove and saltmarsh communities from 1986 to 2015 at Torrens Island within the red circled area. B) Land Cover most likely layer and aerial photography change estimates over the same period for the same area as the photos on the left.

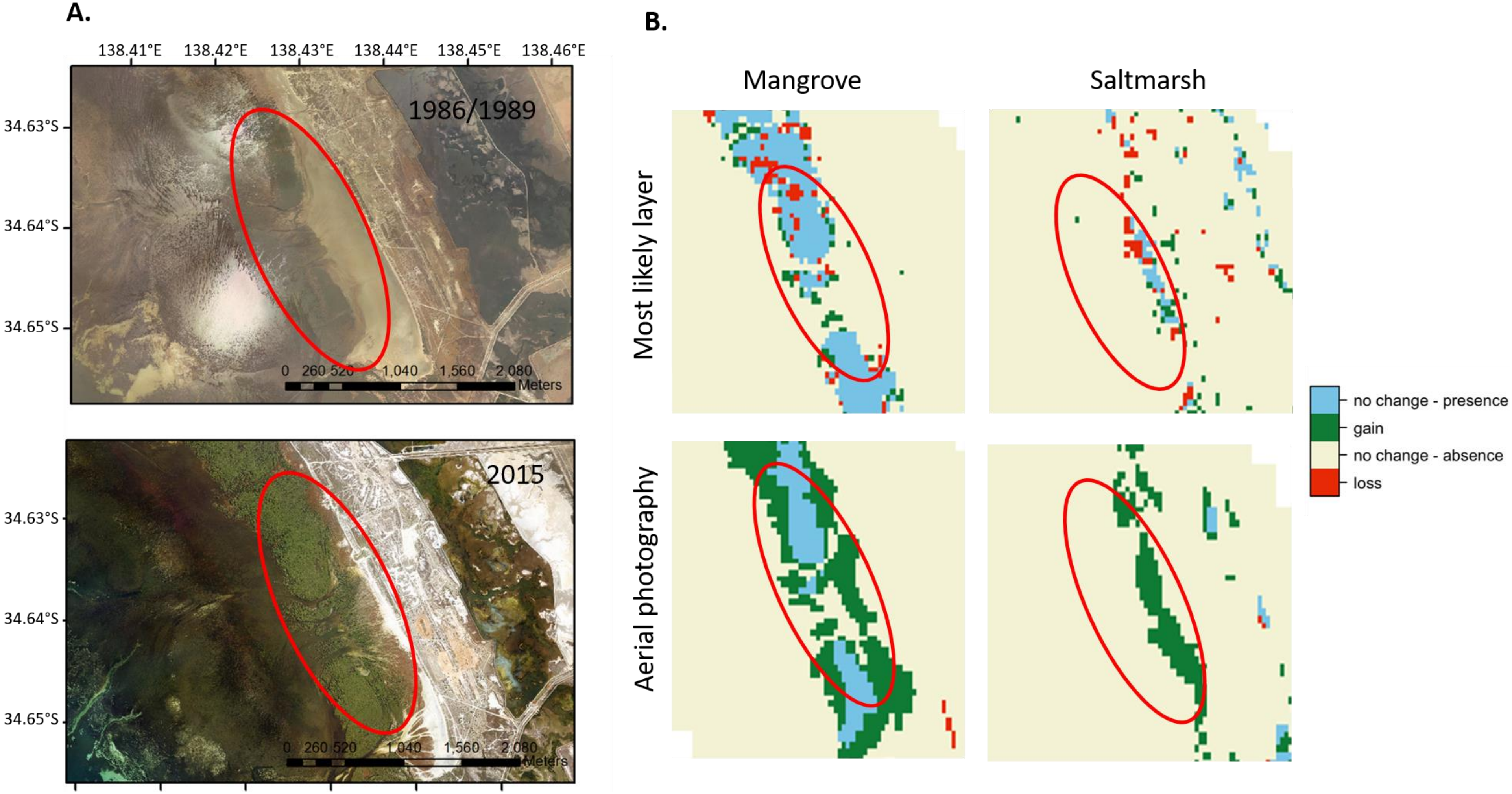

Figure 4. A) Aerial photography showing changes in landward distribution of both mangrove and saltmarsh communities from 1986 and 2015 at the Middle Beach area of interest. B) Land Cover most likely layer and aerial photography change estimates over the same period for the same area as the photos on the left.

4 Discussion

Results of the state-wide analysis of change in mangrove and saltmarsh vegetation in South Australia, based on the SA Land Cover most likely dataset, indicated that there was a small increase in both vegetation types over the period of 1987-2015. However, the variability in the classification (particularly for saltmarshes), along with the results from the external validation using digitised aerial images (See Appendix 1), suggests that the SA Land Cover most likely dataset does not accurately map extent, nor change in the extent, reliably. While this discrepancy appears significant, it does not mean that the SA Land Cover most likely dataset layers are not useful. Satellite remote-sensed data have been used to generate global estimates of mangrove extent (Giri et al. 2011). Conducting these estimates using only aerial photographs would take significantly more time to the point where it may not be feasible. Having broad-scale estimates of coastal vegetation extent based on satellite data can be important to document large scale changes and broadly inform management. As technology evolves, or the SA Land Cover model is improved (particularly by adding more training points), such satellite data may be able to detect finer scale changes. For example, global estimates from Giri et al. (2011) were recently improved by Sanderman et al. (2018) using higher resolution imagery. However, at present, the SA Land Cover most likely dataset appears unreliable for detecting and identifying local scale mangrove and saltmarsh change in South Australia, so state-level estimates should be viewed with these limitations in mind.

Change in mangrove and saltmarsh vegetation was more rigorously estimated by aerial photography. Even so, there are significant limitations to this approach that need to be considered. For example, manually classifying vegetation cover can be difficult due to the spectral characteristics and poor resolution of older photographs, particularly if they are black and white as opposed to colour images. In our study, only two sites could be used for the external validation exercise due to inconsistent temporal coverage of aerial photos in other areas. Low quality data or poor data coverage have previously been noted as an issue when using a range of remotely sensed data types, which can lead to trends being incorrectly attributed due to data artefacts and errors (Friess and Webb 2014). One way we have tried to confirm the results of this study was to refer to field observations for our areas of interest (see Table 13). Some of these studies verify the change reported from the aerial imagery. For example, the changes in mangrove and saltmarsh at Middle Beach (

Figure 4) are confirmed by Cann et al. (2018, 2009) who applied a combination of aerial photography and field observations. Additionally, the increase in mangrove and saltmarsh documented at Torrens Island (Figure 3) was verified through field observations by Coleman et al. (1998, 2017). Field observations can be useful to verify small scale change; however, these data are plagued by limitations relating to disparity in data collection methods; inconsistency in observations; and a need to study the same period through time, which is resource demanding. Varying forms of data and the different ways they are collected can produce different estimates of coastal vegetation change and that the scale of assessment is important for determining the most appropriate data set to use (Mejía-Rentería et al. 2018).

Table 13. A list of field studies, and description of their results, for the areas of interest that we used to externally validate the SA Land Cover dataset. Green represents studies that agreed with the aerial photograph, orange represents studies where changes were before the time period of study.

STUDY	YEAR	METHOD	FINDING SALTMARSH	FINDING MANGROVE
Coleman et al.	2017	Field observation 1994-2014 1989-2015	Middle Beach, Port Gawler extensive loss of Tecticornia arbuscula	Middle Beach mangrove landward regression

			Torrens Island *Sarcocornia quinqueflora* increase and *Tecticornia arbuscula* decrease	Torrens Island mangrove movement into saltmarsh
Cann et al.	2009 and 2018	Aerial photographs and observations 1970s to 2008 (updated to 2018 in later paper)	Middle Beach saltmarsh landward movement	Middle Beach mangrove landward movement
Coleman	1998	Aerial photographs 1949 to 1993	Change 1979-1993 loss of saltmarsh at North Arm creek (within Torrens Island area of interest), 1979-1983 saltmarsh was recolonizing at a similar rate to the loss, however after 1983 recolonisation was not occurring at the same rate and so a significant increase in loss of saltmarsh was recorded	Gain in mangrove 1979-1993, appears to be encroaching on saltmarsh habitat
Hall	1997	Aerial photographs 1935 to 1993, field observations 1994	Le Fevre Peninsula (near Torrens Island) - loss of saltmarsh, due to pollution, human expansion and concrete walls	Loss of mangroves
Bayard	1992	Aerial photographs 1956 - 1992	Not recorded	Near Torrens Island close to Bolivar sewage treatment works outflow, loss of over 250 ha mangroves since 1956
Burton	1982	Aerial photographs 1948-1981	Not recorded	Middle Beach - increase of mangrove seaward and landward

The outcome of assessments of coastal vegetation change can vary depending on the method used, therefore a combined approach using multiple methods is likely to be the most robust way forward. For instance, satellite data can be used to infer broad scale changes that are occurring and identify significant (i.e. relative large) change events such as land clearing for aquaculture (Thomas et al. 2018) and large climate change events (Duke et al. 2017). Aerial photographs can then be applied to these areas to validate the findings and assess their accuracy, particularly at the boundary between mangrove and saltmarsh habitat. We highlight that fine scale change may only be a few hundred metres, however, a few hundred metres of mangrove and saltmarsh loss could in fact be a whole section of coastline, which would leave this area vulnerable to erosion.

Fine scale change can also influence the capacity of coastal habitats for carbon capture and storage, as well as habitat provision as these communities support juvenile fish, insects and small vertebrates (Fotheringham and Coleman 2008, Harbison 2008). Field observations can then add to this body of data, to not only validate the changes observed but also provide species level information. Satellite and aerial photography data cannot (yet) discern changes at the species level (unless there is only a single species present, like for mangroves in South Australia). Hyperspectral imagery technologies are available which have a much finer resolution (up to 1 m) across a greater spectral range, but even these cannot identify species when they are growing intermingled in mixed assemblages (Kuenzer et al. 2011). Therefore, field-based observations could be vitally important to inform species level changes and ensure management policies are correct. For example, satellite and aerial photography may not pick up area changes in saltmarsh vegetation in a particular location, however, this area may still be losing saltmarsh species diversity. This is clearly demonstrated by Coleman et al. (2017) where they documented an increase in *Sarcocornia quinqueflora* and subsequent decrease in *Tecticornia arbuscula* at Torrens Island, which would be documented as a gain or no change of saltmarsh vegetation using satellite and aerial photography data. This change in species composition was attributed to sea level rise which is a threat to saltmarsh diversity as many species require routinely fresher water conditions for sexual reproduction (Saintilan and Rogers 2013). Additionally, the survival of saltmarsh habitats depends on their ability to keep pace with the rates of environmental change occurring and those species more efficient at landward accretion are more likely to survive (Baustian et al. 2012). There is only one species of mangrove in South Australia, *Avicennia marina,* and therefore detection of change in species diversity is not an issue for this vegetation type. Combining the three data collection methods mentioned above would create a multi scale approach to documenting mangrove and saltmarsh change which is not only more accurate but also more informative.

We propose this multi scale approach be applied to discern changes in mangrove and saltmarsh communities in South Australia, especially if this information is going to be used to inform management or to assess carbon accumulation. As there were only relatively small changes detected over time in the state-wide estimates of coastal vegetation change and there was uncertainty around these results, we could not, with confidence, identify past drivers of change. However past changes in the distribution of saltmarsh and mangrove in South Australia have been linked to nutrient pollution (Hall 1997), sewage outflow (Bayard 1992) and sea level rise (Coleman 1998).

This study provides an understanding of the uncertainties associated with documenting change in mangrove and saltmarsh habitats using the classified SA Land Cover dataset. We have shown that the scale of change and method used to assess it need to be considered, as different methods can yield different results. This means that monitoring change in saltmarsh and mangrove ecosystems will require a multi scale approach, which combines a variety of methods for robust detection of trends. Overall, using the most likely layers, we can say that there is unlikely to have been large scale changes in mangrove and saltmarsh extent in South Australia from 1987 to 2015. To detect change using this dataset, however, the scale of change would need to be greater in magnitude than the error in the dataset. Therefore, given the inconsistencies and insensitivity in this data, it's difficult to reach a conclusion.

The evaluation of SA Land Cover dataset proved there are fine scale changes occurring to the spatial cover and distribution of mangrove and saltmarsh ecosystems that require ongoing monitoring efforts. It showed that these were not identified in the change assessment based on the most likely layers of the SA Land Cover dataset. We therefore suggest that future mapping and monitoring of these ecosystems involves additional local-scale external evaluation of the SA Land Cover dataset classification of saltmarsh and mangrove (e.g. for other sites across the state using alternative data sources and comparing patterns of change). We believe this is a practical way forward, especially when relating the area and changes in the distribution of these ecosystems to carbon stocks and accumulation, as the results will be more accurate and robust. If the most likely layers from the SA Land Cover dataset are found to be consistently unreliable in the mapping of saltmarsh and mangrove (after further external evaluation), a dedicated mapping and modelling program for these difficult-to-classify coastal vegetation types may be the best way forward for linking changes in the distribution of these ecosystems to carbon stocks and sequestration.

As noted above, this report focusses primarily on the most-likely layers from the SA Land Cover dataset. Collaborative attempts with DEW and the creators of the Land Cover model to make use of the continuous data layers did not identify any robust approach to directly use the continuous layers when looking for change through time in saltmarsh and mangrove. There may be a need for further work to investigate whether the continuous layers are useful, particularly when trying to understand where and why misclassifications occur in the most likely layers (such as those we identified through comparison with the aerial photographs). This and other investigations should be undertaken so that consistent and accurate separation of land cover classes can be achieved, as the current level of error in the ability of the model most-likely layers to do this (particularly for saltmarsh) will propagate through to uncertainty in state carbon stock estimates. Combined with the uncertainties around the amount of carbon storage and sequestration into South Australian blue carbon ecosystems (Lavery et al. 2019), this could lead to considerable error in overall estimates of blue carbon dynamics.

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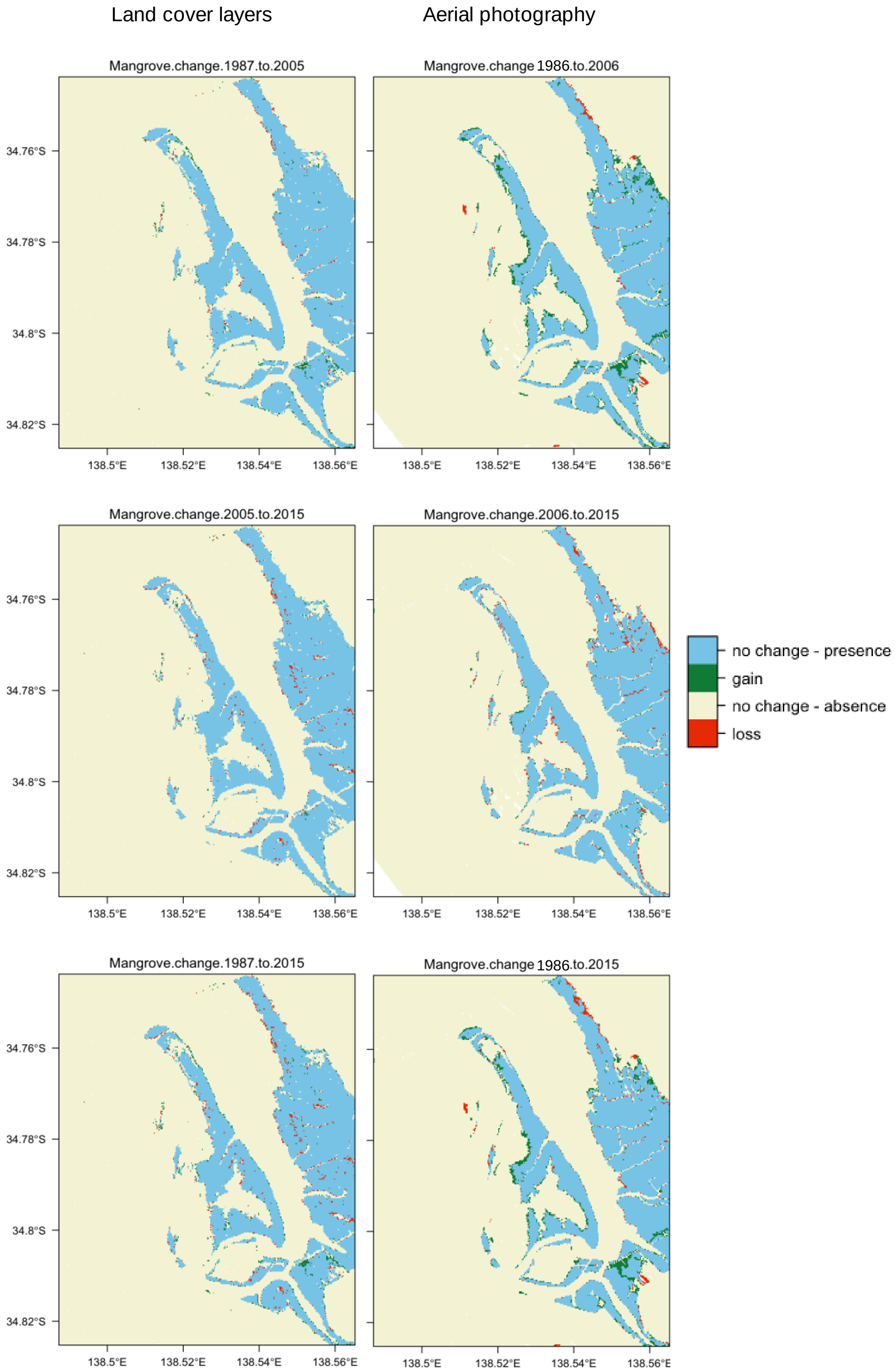
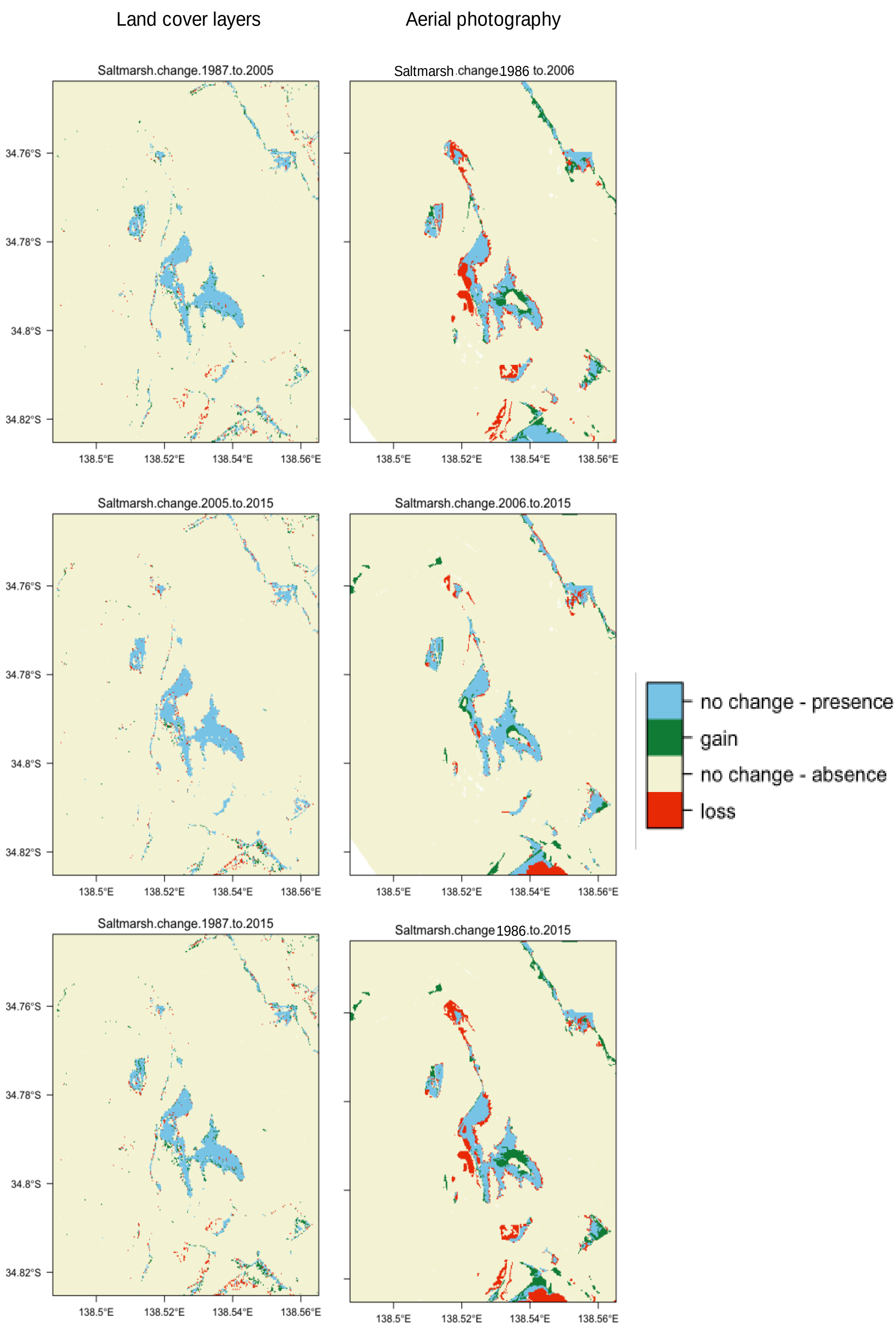
Appendix

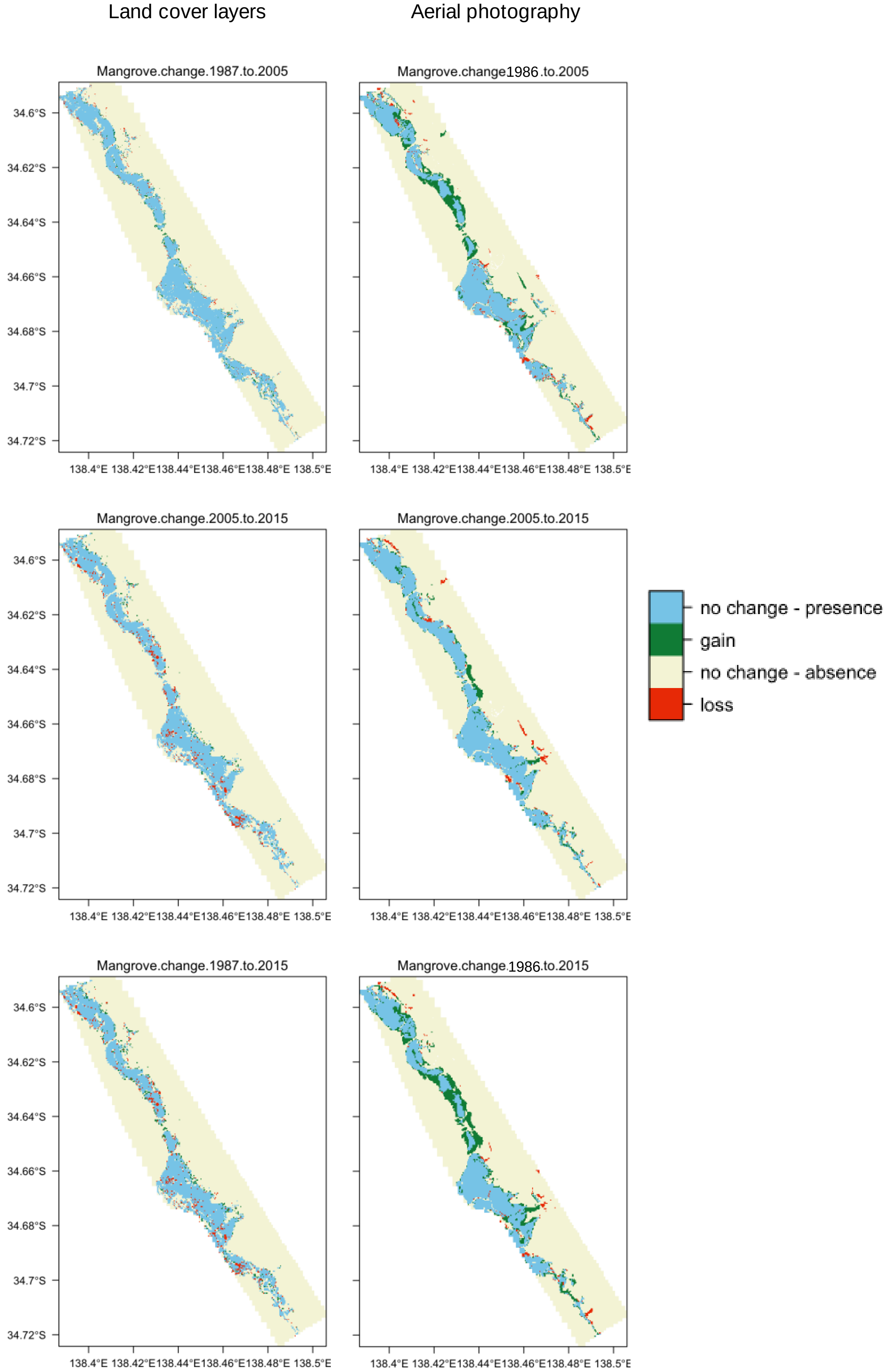
Torrens Island evaluation area change maps for mangrove and saltmarsh

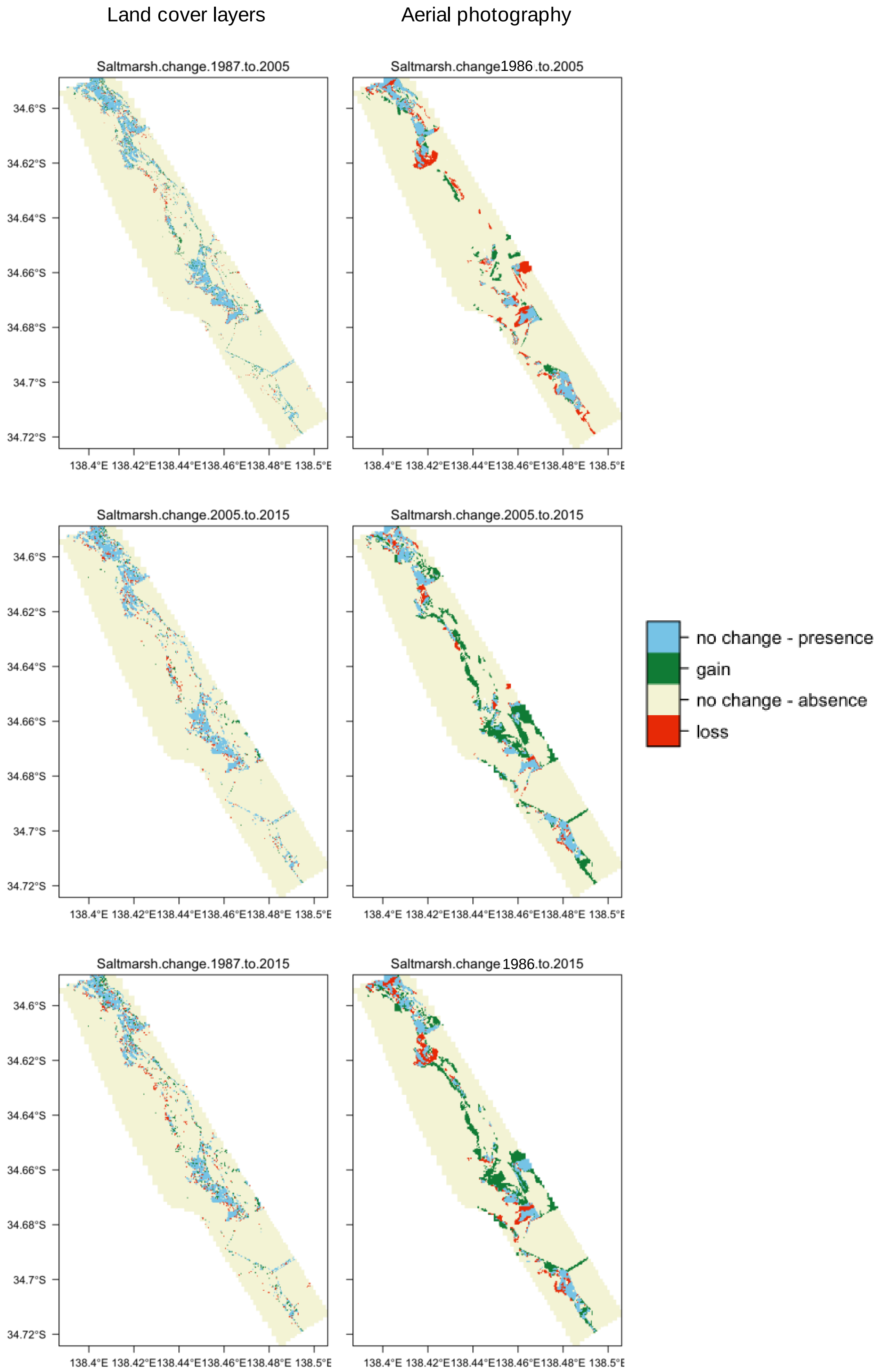




Land cover layers
Aerial photography
Saltmarsh.change.1987.to.2005
Saltmarsh.change1986 to.2006
Saltmarsh.change.2005.to.2015
Saltmarsh.change.2006.to.2015
Saltmarsh.change.1987.to.2015
Saltmarsh.change1986.to.2015
34.76°S
34.78°S
34.8°S
34.82°S
138.5°E
138.52°E
138.54°E
138.56°E
no change - presence
gain
no change - absence
loss

Middle Beach evaluation area change maps for mangrove and saltmarsh





Land cover layers
Aerial photography
Saltmarsh.change.1987.to.2005
Saltmarsh.change1986.to.2005
Saltmarsh.change.2005.to.2015
Saltmarsh.change.2005.to.2015
Saltmarsh.change.1987.to.2015
Saltmarsh.change 1986.to.2015
34.6°S
34.62°S
34.64°S
34.66°S
34.68°S
34.7°S
34.72°S
138.4°E 138.42°E 138.44°E 138.46°E 138.48°E 138.5°E
no change - presence
gain
no change - absence
loss

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