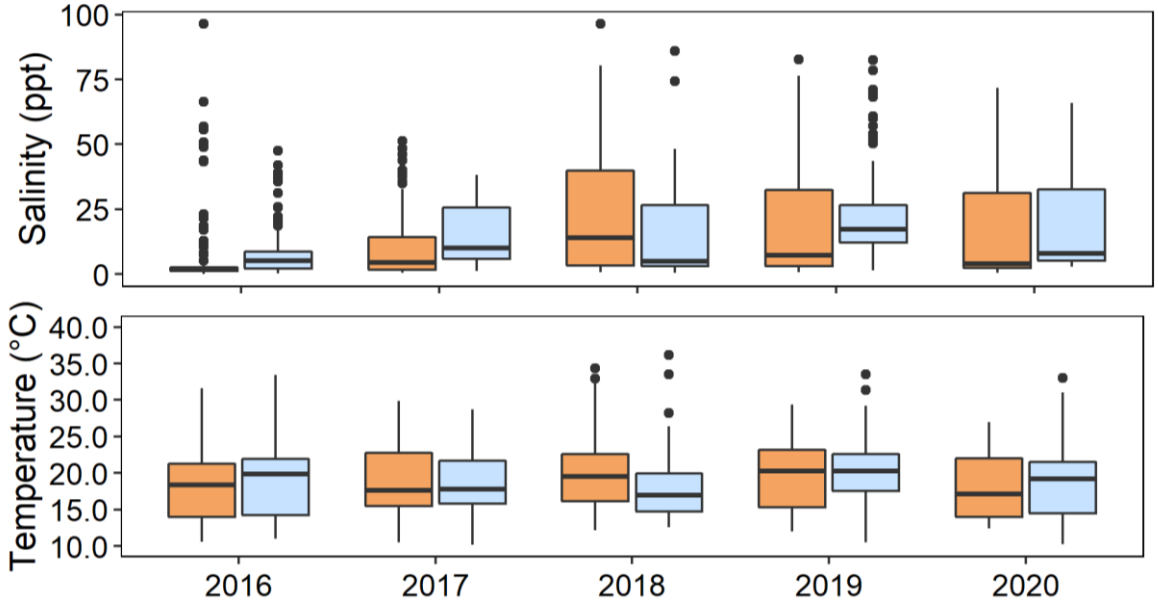
Supplementary material: MABI-D-22-00320



Online Resource Figure 1. Annual bottom salinity and water temperature variation in Vasse (orange) and Wonnerup (blue) estuaries, southwestern Australia. Due to seasonality, depth range of sites is 0.1-1m. Data was collected monthly from water quality monitoring sites within the Vasse and Wonnerup estuaries (n=8, Data source: http://wir.water.wa.gov.au/Pages/Water-Information-Reporting.aspx).

Detailed methods for creation of salinity and temperature datasets for each site

As explained in the main manuscript loggers were installed at each site over the experimental study period and were logging every hour to measure temperature and salinity This supplementary section explains how the data was quality checked and summarised for inclusion in the GAMMs analysis. When there were gaps or missing data in the dataset, if an hourly value differed from the daily mean by ≥ 3 standard deviations and it did not follow the trend of the five preceding and subsequent measurements, then this value was replaced with the average of the value immediately before and after. As a quality check, the readings were compared against the fortnightly *in situ* field measurements and water quality measures of the nearest Department of Water and Environmental Regulation monitoring site of comparable depth (Water Information Reporting). Discrepancies were found at multiple sites from the 17th of December 2019 onwards where logger readings were 0 - 0.01 ppt but *in situ* measures were 36 ppt. Therefore, these data were removed.

Where a site had missing salinity or temperature data due to logger malfunction, the missing data were generated from a regression equation using the observed values from a selected predictor site over the selected time period (Supp Table 1). The sites used to predict the missing data were selected based on the relationship with the strongest adjusted r^2 and, for salinity, the predictions that best matched the *in situ* readings. Missing temperature data were predicted using correlations based on the complete dataset (Supp Table 1). However, for salinity there were weak

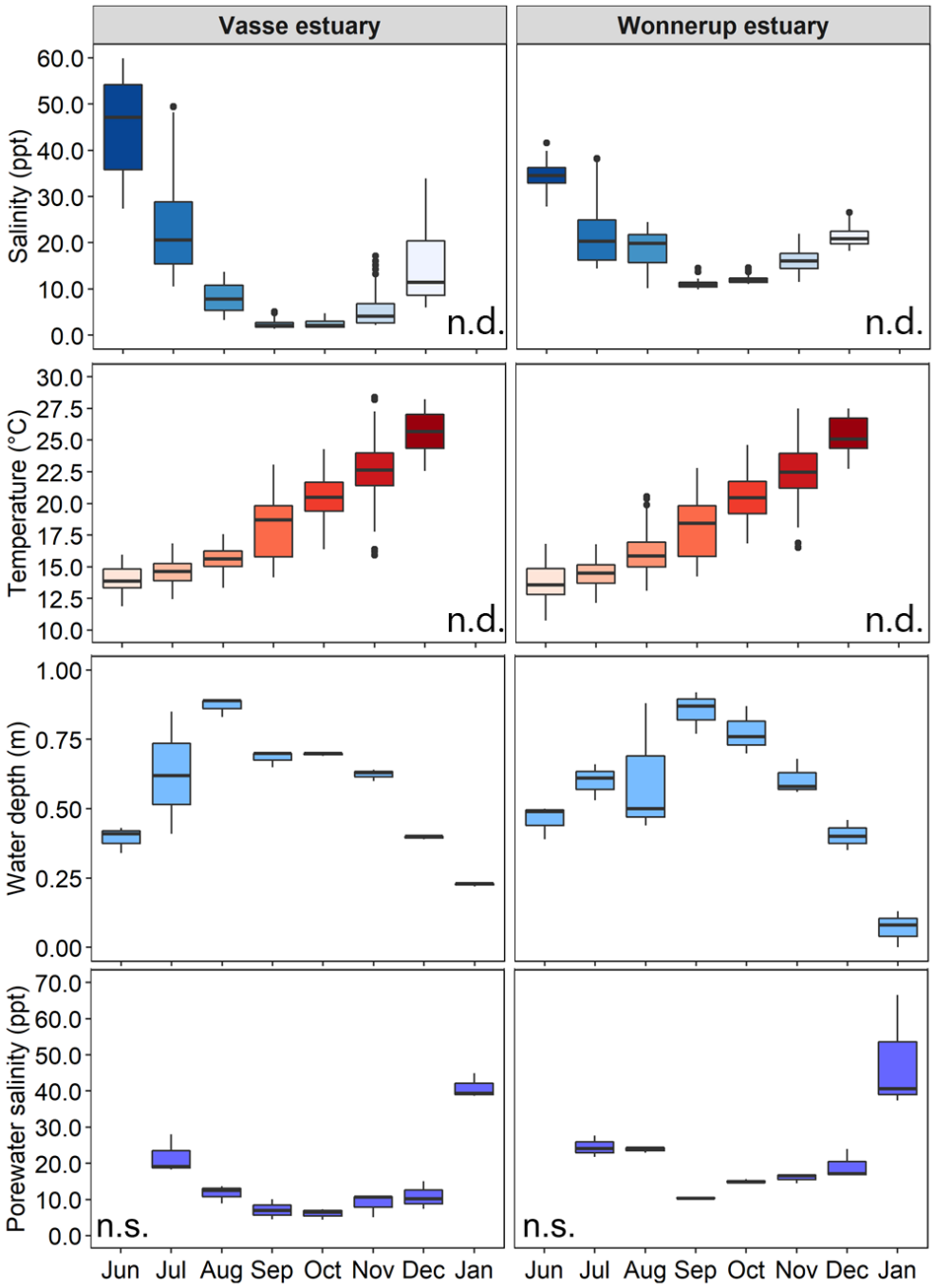
correlations ($r_s < 0.4$) using the whole dataset indicating the patterns in temporal variability among sites were not always consistent. A range of shorter periods either side of the data gaps were assessed and stronger correlations ($r_s > 0.7$) were obtained (Supp Table 1). Logger maintenance (cleaning and data retrieval) during each monitoring trip created an additional data gap in the measurements. Predicted values were not created for these gaps because all six loggers were out of the water at the same time. Datasets were adjusted to ensure all six sites had the same number of readings.

Online Resource Table 1. Data gaps for loggers measuring salinity (S) and temperature (T) at predictor site (x) and dependent / site missing data (y) and the period used to predict the gap based on when the relationship between logger data was strongest (adjusted r and Spearman correlation (r_s) > 0.70) and significant (*) (p=0.05)

	(x)	(y)	Data gap	Period used to predict gap	Adj. r^2	r_s
S	2	1	3/12 - 14/12/19	30/8 - 30/11/19	0.77	0.97*
S	3	2	9/9 - 29/9/19	9/9 - 29/9/19	0.84	0.99*
S	6	4	15/11 - 14/12/19	9/9 - 15/11/19	0.96	0.84*
S	6	5	5/6 - 15/7/19	16/8 - 11/11/19	0.95	0.91*
S	5	6	15/7 - 16/8/19	16/8 - 11/11/19	0.95	0.91*
T	2	1	3 - 14/12/19	16/8 - 31/12/19	0.9	0.96*
T	3	2	5/6 - 15/8/19	16/8 - 16/1/20	0.9	0.99*
T	6	4	15/11 - 14/12/19	5/6 - 15/11/19	0.98	0.98*
T	6	5	5/6 - 15/7/19	16/8 - 16/1/20	0.99	0.99*
T	5	6	15/7 - 16/8/19	16/8 - 31/12/19	0.99	0.99*

Online Resource Table 2. Seagrass monitoring dates and the matching timesteps used for calculation of potential explanatory variables in generalised additive models (GAMs) of seagrass abundance on the date(s) when monitoring occurred.

Seagrass monitoring date	Short-term timesteps	Long-term timesteps
July, 15/7/19	**1:** 1/7 - 15/7/19	**1:** 5/6 - 15/7/19
August, 15/8/19	**2:** 1/8 - 15/8/19	**2:** 16/7 - 15/8/19
September, 13/9/19	**3:** 30/8 - 13/9/19	**3:** 16/8/19 - 13/9/19
October, 16/10/19	**4:** 2/10 - 16/10/19	**4:** 14/9 - 16/10/19
November, 16/11/19	**5:** 2/11 - 16/11/19	**5:** 17/10 - 16/11/19
December, 14/12/19	**6:** 30/11 - 14/12/19	**6:** 17/11 - 14/12/19



Online Resource Figure 2. Environmental conditions in the Vasse and Wonnerup estuaries, southwestern Australia. For benthic salinity and temperature, hourly data was collected by loggers (HOBO U24-002-C) deployed from June to Dec 2019 at three sites within each estuary (n=3). Discrete measures of water depth and porewater salinity (5 cm depth) were also taken monthly from June to January 2020 at the same three sites within each estuary (n=3). 'n.s.' denotes periods not sampled and 'n.d.' denotes no data due to logger malfunction. Boxplots indicate the 25th percentile, median and 75th percentile and whisker ends represent the maximum and minimum data points less than 1.5 times the interquartile range.

Online Resource Table 3. List of environmental variables considered as potential explanatory variables in generalised additive mixed model (GAMM) for life history stages of *Ruppia* spp.

#	Variable name	Description	Temporal scale	**Strongly collinear** ($r_s \geq 0.7$) variables
1	depth_mth	Discrete water depth measurement in	Month prior to sampling	
2	pwater	Discrete porewater salinity (0-5cm interval)	At time of sampling	
3	meanmth_sal	Average salinity	Long-term (~ 32 days prior to sampling)	2, 4, 5, 13, 14, 15, 16
4	minmth_sal	Minimum salinity	"	
5	maxmth_sal	Maximum salinity	"	
6	stderrmth_sal	Std error salinity	"	16
7	ratemth_sal	Rate of change salinity	"	8, 9, 10
8	meanmth_temp	Average temperature	"	7, 9, 10, 11, 17, 18, 19, 20, 21
9	minmth_temp	Minimum temperature	"	
10	maxmth_temp	Maximum temperature	"	
11	stderrmth_temp	Std error temperature	"	
12	ratemth_temp	Rate of change temperature	"	11
13	meanf_sal	Average salinity	Short-term (14 days prior to sampling)	
14	minf_sal	Minimum salinity	"	
15	maxf_sal	Maximum salinity	"	
16	stderrf_sal	Std error salinity	"	
17	ratef_sal	Rate of change salinity	"	
18	meanf_temp	Average temperature	"	
19	minf_temp	Minimum temperature	"	
20	maxf_temp	Maximum temperature	"	
21	stderrf_temp	Std error temperature	"	
22	ratef_temp	Rate of change temperature	"	

Online Resource Table 4. Full list of Generalised Additive Mixed Models

Ungerminated seeds – full list of models (k=4)

Model name	**AICc**	**delta.AICc**	**wi.AICc**	**r2.vals**
meanmth_temp+ratemth_temp	275.53	0.00	0.983	0.94
meanmth_temp	283.82	8.29	0.016	0.90
ratemth_temp+stderrmth_sal	290.07	14.54	0.001	0.89
ratemth_temp	291.09	15.56	0.000	0.87
null	293.53	18.00	0.000	0.82
stderrmth_sal	293.69	18.16	0.000	0.84
depth_mth	296.77	21.24	0.000	0.82
meanmth_sal	298.05	22.52	0.000	0.84

Germinated seeds (k = 3)

Model name	AICc	delta.AICc	wi.AICc	r2.vals
meanmth_temp	207.02	0.00	0.439	0.16
meanmth_temp+ratemth_temp	207.49	0.47	0.348	0.21
null	210.82	3.80	0.066	0.07
depth_mth	211.21	4.19	0.054	0.06
stderrmth_sal	212.38	5.36	0.03	0.02
ratemth_temp	212.64	5.62	0.026	0.08
meanmth_sal	212.72	5.69	0.025	0.05
ratemth_temp+stderrmth_sal	214.38	7.36	0.011	0.10

Seedlings

Model name	AICc	delta.AICc	wi.AICc	r2.vals
ratemth_temp+stderrmth_sal	259.50	0.00	0.771	0.45
ratemth_temp	262.38	2.87	0.183	0.36
meanmth_temp+ratemth_temp	265.69	6.19	0.035	0.36
null	270.44	10.94	0.003	0.10
stderrmth_sal	270.62	11.12	0.003	0.06
depth_mth	271.33	11.82	0.002	0.04
meanmth_temp	271.90	12.40	0.002	0.03
meanmth_sal	272.32	12.82	0.001	0.01

Seagrass PVI

Model name	AICc	delta.AICc	wi.AICc	r2.vals
meanmth_temp+ratemth_temp	123.46	0.00	0.769	0.77
meanmth_temp	125.86	2.40	0.231	0.73
meanmth_sal	146.98	23.53	0	0.53
ratemth_temp+stderrmth_sal	147.38	23.92	0	0.57
stderrmth_sal	149.60	26.14	0	0.45
depth_mth	150.38	26.93	0	0.47
ratemth_temp	165.39	41.93	0	0.15
null	168.65	45.19	0	0.03

Average biomass (k=3)

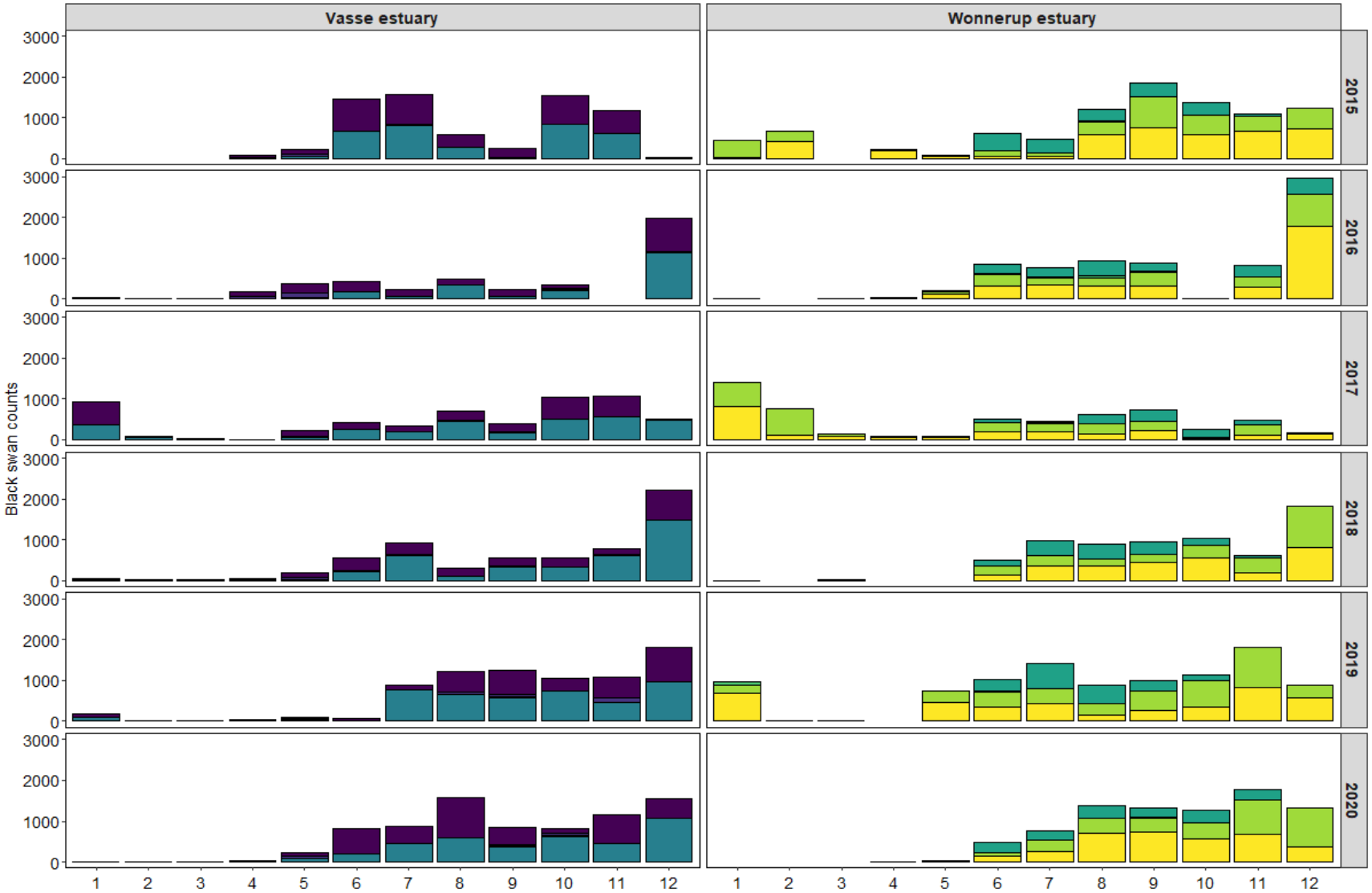
Model name	AICc	delta.AICc	wi.AICc	r2.vals
stderrmth_sal	59.37	0.00	0.535	0.20
depth_mth	61.43	2.06	0.191	0.13
null	61.87	2.50	0.153	0.38
depth_mth+meanmth_sal	64.06	4.69	0.051	0.11
meanmth_sal	65.10	5.73	0.031	0.33
ratemth_temp	65.69	6.32	0.023	0.37
meanmth_temp	66.53	7.16	0.015	0.38
meanmth_sal+ratemth_temp	73.30	13.93	0.001	0.46

Online Resource Table 5. Average swan abundance average calculated from count data collected in winter, spring and summer (June to January) from sites in the Vasse (n=4) and Wonnerup (n=4) estuaries. Data source: (Williams and Taylor 2015)

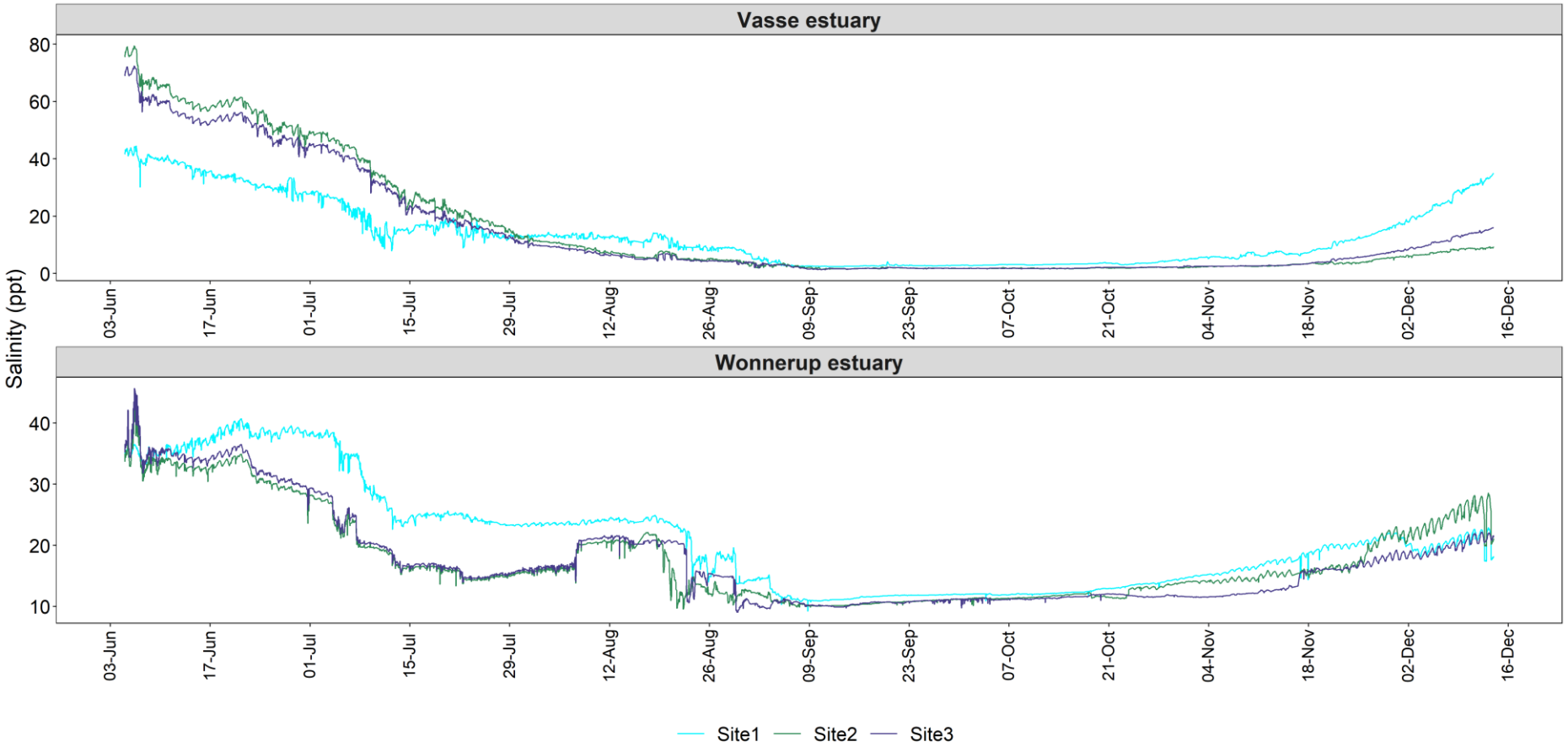
Season of sampling	Average	Standard error
2015-16	313.39	41.41
2016-17	232.49	30.52
2017-18	158.02	22.99
2018-19	171.71	19.47
2019-20	342.11	30.40

Online Resource Table 6. Estimated potential impact of swan grazing on *Ruppia*. Averages were calculated from data collected in November in 2018, 2019 and 2020 from sites in the Vasse (n=5) and Wonnerup estuaries (n=5). Data source: Department of Water and Environmental Regulation. *Consumption rate based on (Dos Santos and others 2012).

Average seagrass biomass (g DW m^{-2})	Average total swan abundance in system	Daily food intake (at 394 g $swan^{-1}$ day^{-1*} ($t\ d^{-1}$)	Daily *Ruppia* consumption as proportion of the total (%)	Days taken to graze out estuary (d)	20% of total biomass (tonnes)	Time to graze 20% (d)	No. of swans to graze 20% in a month
185	2,411	0.95	0.51	197	37	39	3,122



Online Resource Figure 3. Black swan count data collected monthly (2015-2020) from sites in the Vasse (n=4) and Wonnerup (n=4) estuaries. Different colours represent data collected at different sites. Data source: (Williams and Taylor 2015)



Online Resource Figure 4. Hourly salinity (ppt) plots from seagrass monitoring sites during June to December 2019 within the Vasse and Wonnerup estuaries, southwestern Australia.

Online Resource Figure 5. Hourly temperature (°C) plots from seagrass monitoring sites during June to December 2019 within the Vasse and Wonnerup estuaries, southwestern Australia.