Native and non-native fishes in wetlands of the Swan Coastal Plain, Western Australia

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Fish populations in enclosed wetlands on the Swan Coastal Plain, Western Australia, were sampled to determine their species composition and distribution. Many wetlands in this area previously classed as perennial were found to not contain permanent freshwater during the sampling period between January and July 2010. Of the 113 wetlands that contained water, 76% also housed fish. Of those inhabited wetlands, few contained only native species (12%), while the many contained either both native and non-native fishes (45%) or non-native fishes only (42%). Only seven wetlands out of the 113 contained only obligate freshwater fishes native to the region. Overall, numbers of fish were dominated by the non-native species *Gambusia holbrooki* (78.6%), with the native euryhaline *Pseudogobius olorum* being next most abundant (16.2%). *Galaxias occidentalis, Leptatherina wallacei, Nannoperca vittata, Bostockia porosa* and *Galaxiella nigrostriata* were the only other native fish species caught. Wetlands with higher salinity typically contained a greater proportion of *P. olorum* and fewer *G. holbrooki*. *Nannoperca vittata* were only relatively abundant in wetlands containing dense riparian and aquatic vegetation. These trends indicated that environmental factors may convey a competitive advantage for native over non-native species, e.g. salinity for *P. olorum* and vegetation for *N. vittata*. Overall, this study highlights the paucity of lentic systems on the southern Swan Coastal Plain in which native fish populations exist without non-native competitors.

KEYWORDS: south-western Australia, freshwater fish, alien, feral

INTRODUCTION

The wetlands of the Swan Coastal Plain (SCP) in south-western Australia form a series of water bodies that are now largely isolated from each other, a situation exacerbated by the metropolitan and suburban areas by which many are now surrounded (Balla & Davis 1993). Over the past *ca* 70 years, concerns have been expressed regarding a drying trend for previously perennial water bodies. These concerns were first raised due to their agricultural value as a water source for crops and livestock (Havel 1975), but continues in response to their conservation and aesthetic value (Balla & Davis 1993). In addition to the climatically-driven drying trend (CSIRO 2009), many wetlands on the SCP have been actively cleared, drained or filled for reclamation of land, resulting in the loss of up to 80% of the original number (Bekle & Gentilli 1993; Brearley 2005). Concomitantly, groundwater abstraction and modifications to catchments have resulted in many seasonal wetlands becoming dry year round, and some perennial wetlands becoming seasonally or permanently dry (Balla & Davis 1993). This loss of permanent water prevents the survival of most fish in these lentic ecosystems. Other threatening processes for these wetlands include the introduction of non-native fauna (Morgan *et al.* 2004; Beatty & Morgan 2013), altered water quality (Davis *et al*. 1993) and urbanisation (Balla & Davis 1993; Davis & Froend 1999).

Eleven native fishes have been recorded from the freshwater lotic and lentic systems of the SCP (Morgan *et al.* 2011). Four are obligate freshwater inhabitants, *Nannoperca vittata* (Castelnau, 1873), *Bostockia porosa* Castelnau, 1873, *Tandanus bostocki* Whitley, 1944 and *Galaxias occidentalis* Ogilby, 1899 (Allen *et al.* 2002). Three others, *Nannatherina balstoni* Regan, 1906, *Galaxiella nigrostriata* (Shipway, 1953) and *Galaxiella munda* McDowall, 1978 have only been reported sporadically from the SCP but are more common in the southern parts of south-western Australia (Morgan *et al.* 1995, 1998, 2011; Smith *et al.* 2002a; Galeotti *et al.* 2010). Likewise, the diadromous species *Geotria australis* Gray, 1851 is typically found in more southern locations (Morgan *et al*. 1998). The remaining three species, *Afurcagobius suppositus* (Sauvage, 1880), *Pseudogobius olorum* (Sauvage, 1880) and *Leptatherina wallacei* (Prince, Ivantsoff & Potter, 1982), have been found in the same waterbodies (Allen *et al.* 2002) but are euryhaline species, occurring in both fresh and estuarine habitats (Morgan *et al.* 1998, 2011; Morgan & Gill 2000). All of the above species, except *P. olorum* and *G. australis*, are endemic to the Southwestern Province (Morgan *et al.* 2011). It should also be noted that as *G. australis* undertakes migrations, it predominantly inhabits lotic systems, not enclosed wetlands, and will not be considered further in this document.

Several non-native freshwater fishes have been reported from the SCP, with *Gambusia holbrooki* Girard, 1859 being by far the most widely distributed (Morgan *et al.* 2004). Other non-native species reported for this area include, *Amatitlania nigrofasciata* (Gunther, 1867), *Bidyanus bidyanus* (Mitchell, 1838), *Carassius auratus* (Linnaeus, 1758), *Cyprinus carpio* Linnaeus 1758, *Geophagus brasiliensis* (Quoy & Gaimard, 1824), *Macquaria ambigua* (Richardson, 1845), *Oncorhynchus mykiss*

(Walbaum, 1792), *Perca fluviatilis* Linnaeus, 1758, *Phalloceros harpagos* Lucinda, 2008, *Puntius conchonius* (Hamilton, 1822), *Leiopotherapon unicolor* (Günther, 1859) *Salmo trutta* Linnaeus, 1758 and *Tandanus tandanus* (Mitchell, 1838) (Beatty & Morgan 2013; Duffy *et al*. 2013).

While the distribution of freshwater fishes of south-western Australia has been relatively well documented, emphasis has been placed on those in rivers and streams (e.g. Morgan *et al.* 1998, 2004, 2006). Comparatively little work has been documented on the fish fauna of the perennial lentic water bodies in south-western Australia, particularly those of the SCP. Published reports include those by Major (2009), which documented fishes from 29 urban wetlands, and Davis *et al.* (1993), which recorded fishes caught incidentally during sampling for macroinvertebrates in 37 wetlands. Fairhurst (1993) also studied the feeding ecology of several species and single-species studies were also produced for *G. nigrostriata,* incorporating SCP wetlands (Smith 2002a, b; Galeotti *et al.* 2010). Duffy *et al*. (2013) presented the first record for Western Australia of the non-native species, *Amatitlania nigrofasciata* in a natural water body as well as providing an up-to-date catalog of non-native freshwater fish species in the region. While the information that these studies collectively provide on the fish fauna in SCP wetlands is valuable, there remain significant gaps in the body of knowledge in this area.

The aim of the current study was to address this paucity of information through a survey of the perennial wetlands of the SCP to determine the current distribution of both native and non-native fishes. As these water bodies are largely isolated from each other, it was expected that they would be relatively resilient to the spread of non-native fishes to interconnected rivers and streams. It was expected that most sites that held permanent water would contain populations of native fishes and that native fishes would be more widely distributed than non-native species. Additionally, the study aimed to explore the relationships between the relative abundance of the fish species and physical and chemical attributes of the wetlands. Information gathered during this survey will enable better prioritisation and management of water bodies, potentially including rehabilitation, non-native eradication, and feasibility assessments for restocking with native species.

METHODS

Study area and site selection

The SCP is located on the south-western coast of Western Australia. It is a narrow (30 km at its widest point) stretch of land bounded by the Indian Ocean to the west and the Darling Escarpment to the east. The region extends from Jurien Bay, approximately 600 km south to Cape Naturaliste (Cummings & Hardy 2000) and contains approximately 80% of the human population of Western Australia (Australian Bureau of Statistics 2012). The locations of the recorded perennial wetlands within the boundaries of the SCP were extracted from the Geomorphic Wetlands Swan Coastal Plain Database (Department of Environment and Conservation 2011), and overlayed on the most recent aerial photography available through various sources (Landgate, Google earth and others). The wetlands that appeared to contain permanent water were identified from those combined data sets. In many cases, individual wetlands were found to be part of small contiguous wetland complexes, each of which were subsequently considered as a single water body for sampling and analyses. Using those defined units, water bodies were discrete and physically isolated from each other. The subset of wetlands most likely to contain water were visited in the field to validate whether a permanent water body existed at that location, and when water was present, sampling for fish was conducted. Where possible, wetlands were selected from diverse locations throughout the study area to give a more representative spatial coverage of the wetlands and their fish fauna.

Sampling

Fish were sampled from 113 wetlands between January and July 2010. Climate data for the Perth metropolitan area indicated that the preceding year, 2009, was the second hottest to date (mean temperature 25.0°C, 0.6°C above the long term average) and among the 10 driest on record (annual rainfall = 608.5mm, 245.8mm below the long term average) (Bureau of Meteorology 2010).

Fish were captured using fyke nets which comprised an unbaited, 5 m single wing with 4 mm knotless mesh. Wing drop was sufficient to extend from the surface to the substrate. Up to four nets were set in some of the larger wetlands, whereas in smaller water bodies only a single net was set. They were positioned to sample both the shallow and deeper central parts of the water body. Nets were set during daylight hours, left overnight and retrieved the following day; resulting in an approximately equal soak time for each location. When nets were retrieved, fish were identified according to Allen *et al.* (2002), counted and where possible, native fish were returned to the water alive. Counts were semi-quantitative, with numbers under 200 being directly counted while numbers over 200 were estimated to the nearest 50 individuals. Fyke nets were used as a standardised sampling device due to their efficiency and as other sampling methods such as electrofishing and seine nets were inappropriate or impractical for use in many locations surveyed. The limitations of and biases introduced through using this single gear-type are acknowledged and include gear selectivity and reliance on active fish movement.

Several abiotic characteristics were recorded for each wetland including water depth (m), temperature (°C), pH, salinity (‰), dissolved oxygen (mg/L), and Secchi depth (m). The coverage of riparian vegetation of the wetland as a whole was noted, and given a score between 1 and 6 where 1 represented completely bare, and 6 represented dense fringing vegetation extending into emergent and submerged aquatic vegetation (*sensu* Keighery 1991; Major 2009). Note that vegetation was scored from a habitat complexity perspective, and as such the composition in terms of native or introduced species was not considered.

Analyses

The number of each fish species caught from each wetland was standardised to individuals/net to allow comparison across all locations. Prior to further analysis, abundances of fishes were $\log_{10}$ transformed due to the skewed nature of the abundance data as was evident on inspection of draftsmans plots of the data. Salinity was the only abiotic parameter that required (square-root) transformation. The abiotic data set was normalised prior to subsequent analyses to allow the abiotic factors measured in different units to be on the same scale and to contribute equally to the analyses.

One-way Analysis of Similarity (ANOSIM) tests were used to determine if the abiotic characteristics of the wetlands differed significantly according to whether they were inhabited by native only, non-native only, native-dominated mixed, or non-native dominated mixed assemblages. When significant differences were detected using ANOSIM, Similarity Percentages (SIMPER) was employed to determine which of the abiotic characteristics was responsible for those differences.

In order to determine if significant relationships existed between the compositions of the fish assemblages and the abiotic characteristics of the wetlands, a BioEnv test was employed. This test matched the rank similarity of the wetlands based on the abundance of the fish species present (Bray-Curtis similarity) with comparable matrices constructed for every combination of the six abiotic characteristics (Euclidian distance). The variable, or group of variables, that provided the best match to the matrix based on the fish assemblages was then determined. ANOSIM, SIMPER and BioEnv tests were all conducted using PRIMER v6 (Clarke & Gorley 2006).

RESULTS

Sampling locations and dry wetlands

The Geomorphic Wetlands Swan Coastal Plain Database indicated that more than 4,000 perennial wetlands exist on the SCP. Comparison of aerial photography and the wetlands database indicated only *ca* 2,000 discrete water bodies were present, with many wetland complexes containing several that may be seasonally contiguous. Only 806 of those discrete water bodies appeared to contain water with the majority of these occurring on the southern half of the SCP (Figure 1). Of those 806 wetlands, 366 were visited in the field, however, many that appeared to contain water from the aerial photographs were actually dry during the sampling period (89 wetlands; 24%; Figure 1) or were inaccessible (164 wetlands; 45%). Both the elevated temperature and decreased rainfall during the preceding year are likely to have contributed to the very large number of dry wetlands observed.

Consequently, of the *ca* 2,000 discrete mapped perennial wetlands, 113 were sampled for fish. The mean salinity in these wetlands was low (2.3 ‰, SD=5.4 ‰), but ranged between 0 and 33 ‰. The mean depth was only 1.2 m (SD=0.8 m) but varied considerably with several very shallow (0.2 m) and deep (4 m) wetlands sampled.

Fish fauna

Fish were caught in 76% (n=86) of the 113 wetlands sampled. Non-native fishes were present in a greater proportion of inhabited wetlands (86%, n=75) than native fishes (57%, n=50). Likewise, there were more wetlands that contained exclusively non-native fishes (42%, n=36) than exclusively native fishes (12%, n=11) (Table 1; Figure 2a). Mixed assemblages containing both native and non-native species were found in 45% of inhabited wetlands (n=39). When they co-occurred, native fish outnumbered non-native fish in 56% of wetlands, the non-natives were more abundant in 26%, while the remaining 18% of wetlands contained native and non-native fish in approximately equal numbers. The distribution data for all fish species in this study are maintained by the Western Australian Department of Fisheries in the

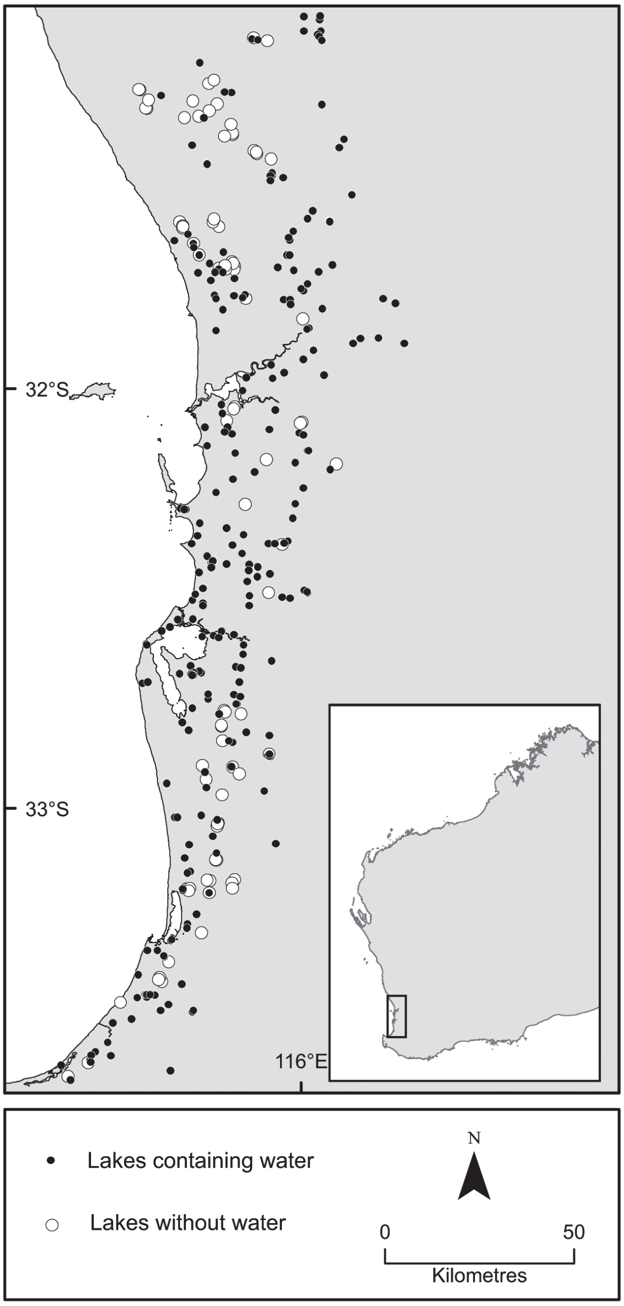

Figure 1 Map of the southern Swan Coastal Plain showing the location of those water bodies which were visited in the field and either confirmed to hold water or found to be dry. Inset showing the location of the study in relation to Western Australia.

Table 1 The details for each wetland sampled including the Geomorphic Wetlands database reference number, latitude and longitude of sampling area and the presence or absence of each of the fish species. N.B. Presence is denoted with an "X". Species codes are: *Po* = *Pseudogobius olorum*, *Go* = *Galaxias occidentalis*, *Lw* = *Leptatherina wallacei*, *Nv* = *Nannoperca vittata*, *Bp* = *Bostockia porosa*, *Gn* = *Galaxiella nigrostriata*, *Gh* = *Gambusia holbrooki*, *Td* = *Tandanus tandanus*, *Lu* = *Leiopotherapon unicolor*, *Ca* = *Carassius auratus*, *Pc* = *Puntius conchonius*, *Xh* = *Xiphophorus hellerii*, *Gb* = *Geophagus brasiliensis*.

Geomorphic wetlands identification number	Latitude	Longitude	Native fishes						Introduced fishes						
			Po	*Go*	*Lw*	*Nv*	*Bp*	*Gn*	*Gh*	*Td*	*Lu*	*Ca*	*Pc*	*Xh*	*Gb*
41BN 1269	-33.60127	115.49864	X						X						
41BN 1274	-33.61232	115.42963	X												
41BN 685	-33.64800	115.45157		X											
41BQ 3700	-33.62572	115.69027													
42BO 3159	-33.55868	116.54061	X	X					X						
42BO 734	-33.51222	115.55304	X						X						
43BP 1041	-33.45226	115.61112		X					X			X			
43BP 3157	-33.45146	115.63401	X						X						
43BP 3684	-33.44447	115.63164							X			X			
43BP 3977	-33.44432	115.62983							X						
43BQ 2375	-33.41926	115.71635							X						
43BQ 2382	-33.48620	115.74297													
44BP 3991	-33.39767	115.61342							X						
44BQ 2376	-33.35276	115.67501	X						X			X			
44BQ 2901	-33.35518	115.67534	X						X			X			
45BR 704	-33.25366	115.75207	X	X					X						
47BQ 725	-33.08750	115.73471							X						
48BR 4215	-33.01770	115.76375													
49BS 1933	-32.92063	115.85497													
50BS 3598	-32.84357	115.83784							X						
50BT 1684	-32.87859	115.92829													
51BQ 3870	-32.81488	115.73280							X			X			
51BR 2517	-32.77632	115.80560		X			X								
51BS 2254	-32.75301	115.84889		X											
51BS 493	-32.75280	115.84637							X						
52BR 202	-32.91459	115.77197													
52BR 667	-32.67739	115.76331													
52BS 2412	-32.73009	115.84131							X						
52BS 580	-32.70030	115.85358							X						
53BP 2039	-32.60923	115.63214													
53BP 2497	-32.61155	115.63304													
53BQ 294	-32.66070	115.73763													
53BR 3075	-32.59005	115.79304	X						X						
53BS 2564	-32.61234	115.86475	X	X											
53BS 666	-32.58763	115.84092													
54BQ 1175	-32.50361	115.74268							X						
54BQ 2661	-32.57764	115.66867							X						
54BQ 2720	-32.50588	115.74193							X						
54BQ 3216	-32.55074	115.70766	X						X						

Geomorphic wetlands identification number	Latitude	Longitude	Native fishes						Introduced fishes						
			Po	*Go*	*Lw*	*Nv*	*Bp*	*Gn*	*Gh*	*Td*	*Lu*	*Ca*	*Pc*	*Xh*	*Gb*
54BQ 3358	-32.55000	115.74341							X						
54BQ 475	-32.56871	115.68805	X												
54BR 1192	-32.51239	115.76736													
54BR 2731	-32.57835	115.81307	X												
54BR 3583	-32.51766	115.76680													
54BR 594	-32.57922	115.81137	X												
55BQ 4132	-32.49172	115.74962							X						
55BR 1174	-32.43834	115.75815							X				X		
55BR 234	-32.47692	115.76752				X			X						
55BR 3816	-32.47646	115.76752				X			X						
55BS 3113	-32.41930	115.87774		X					X						
55BT 4165	-32.49785	115.95612							X						
56BQ 3854	-32.37090	115.73952													
56BR 3047	-32.35155	115.75377							X			X			
56BS 1741	-32.39411	115.86131							X						
56BS 2562	-32.37371	115.83749	X	X					X						
56BT 1364	-32.36514	115.96985	X	X		X									
56BT 1975	-32.37282	115.95471													
56BT 258	-32.37011	115.92331													
57BQ 3299	-32.28821	115.72715	X						X						
57BR 210	-32.33315	115.82369							X						
57BR 2791	-32.32152	115.76017							X			X			
57BT 120	-32.31004	115.98153													
57BT 2404	-32.27560	115.98720							X						
58BR 897	-32.24918	115.79916													
58BT 2487	-32.17700	115.98745							X			X			
58BU 1917	-32.23802	116.00669		X								X			
59BR 2800	-32.13765	115.77780	X						X						
59BR 3490	-32.09271	115.77153							X						
59BS 2770	-32.15544	115.84384													
59BS 673	-32.10968	115.83593							X					X	
59BT 213	-32.10698	115.99697	X	X		X			X						
59BT 514	-32.09844	115.92530	X			X			X		X				
59BU 1455	-32.11205	116.00608													
60BR 1652	-32.03898	115.81144							X	X					
60BR 4093	-32.05991	115.81344							X				X		
60BS 4073	-32.00628	115.86241							X						
60BT 2573	-32.05207	115.93929	X						X						
61BS 314	-31.97401	115.87018							X						
61BT 1395	-31.94445	115.92949	X						X						
61BT 3562	-31.97662	115.93341							X						
61BU 2118	-31.93131	116.00663		X					X						

Table 1 (cont.)

Geomorphic wetlands identification number	Latitude	Longitude	Native fishes						Introduced fishes						
			Po	*Go*	*Lw*	*Nv*	*Bp*	*Gn*	*Gh*	*Td*	*Lu*	*Ca*	*Pc*	*Xh*	*Gb*
62BU 1930	-31.91009	116.03049							X						
62BU 2244	-31.85707	116.01985	X	X					X						
62BV 1401	-31.88168	116.14259							X						
63BR 201	-31.77872	115.79568	X						X						
63BR 2292	-31.78688	115.79922	X						X						
63BR 4092	-31.81317	115.81540	X						X						
63BS 2658	-31.78506	115.86143							X						
63BS 370	-31.77775	115.86774													
63BT 1508	-31.78958	115.97501					X		X						
63BT 1964	-31.78941	115.95967							X						
63BT 3729	-31.79951	115.97555		X		X	X								
63BU 3197	-31.75221	116.01691		X					X						
63BU 3523	-31.76816	116.00563	X						X						X
63BU 864	-31.76339	116.00152													
63BW 129	-31.78697	116.19564		X											
64BR 1319	-31.74369	115.78527	X						X						
64BR 4010	-31.71642	115.80421							X						
64BR 899	-31.72525	115.75573							X						
64BT 306	-31.71931	115.98397				X									
65BQ 3745	-31.63388	115.73196							X						
66BV 1605	-31.53905	116.12167	X	X			X		X						
67BS 467	-31.42507	115.88992	X	X	X				X						
67BT 2202	-31.44533	115.93795				X	X								
67BT 3609	-31.49427	115.93190													
67BT 977	-31.49903	115.95793		X			X	X	X						
67BV 1582	-31.42744	116.09189	X	X	X	X	X		X						
68BV 1854	-31.40727	116.10285	X	X	X	X	X		X						
70BR 3850	-31.86360	115.79817		X	X							X			
70BS 3077	-31.16757	115.88458													
97BM 57	-28.94392	115.38383													
98BM 8	-28.91187	115.41218													
98BN 2061	-28.89173	115.43041													

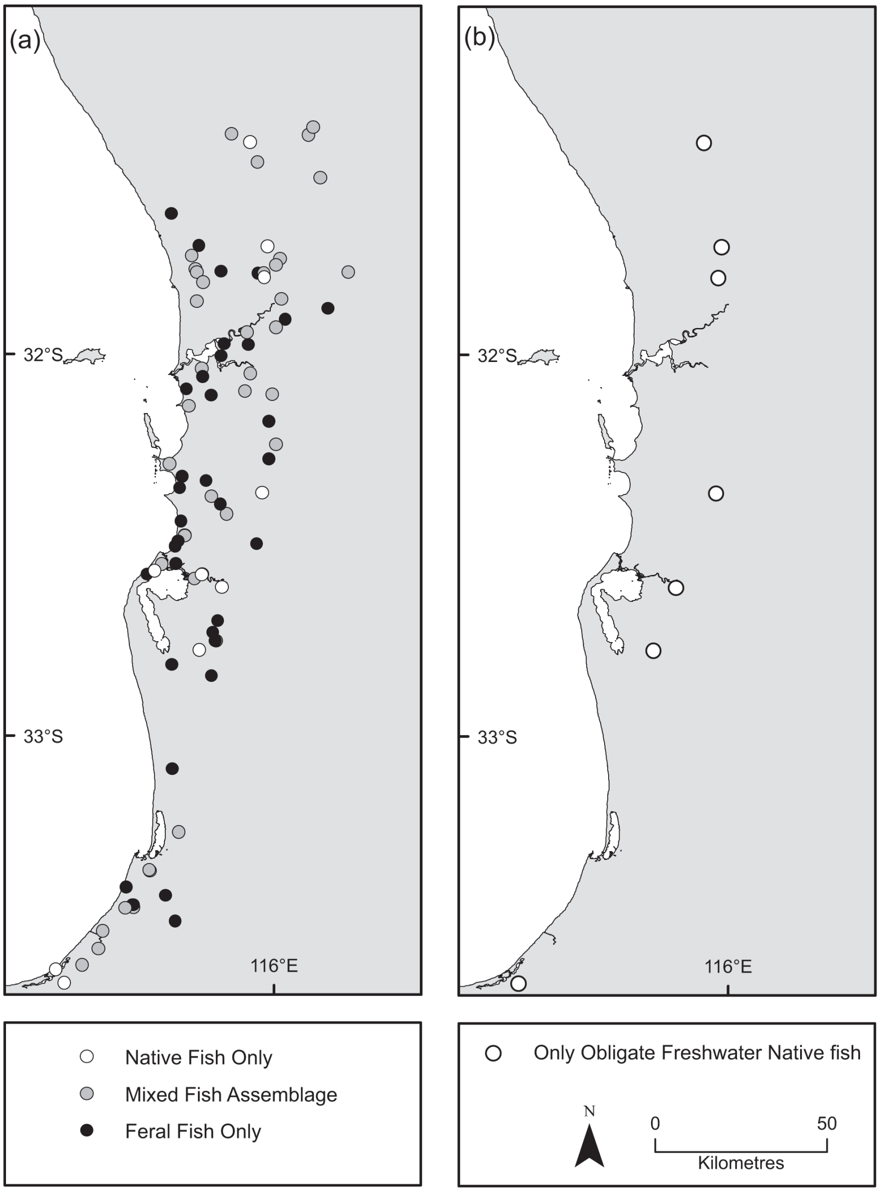

Figure 2 Map of the southern Swan Coastal Plain showing the location of those water bodies which (a) were sampled and contained fish, coded for the composition of the fish assemblages (native only, mixed or non-native only), and (b) contained only native, obligate freshwater species.

publicly available online Freshwater Fish Distribution Database (Department of Fisheries 2012).

The total number of fish caught during this study was *ca* 62,200 individuals and overall, non-native fish outnumbered native fish at a ratio of almost 4:1 (Table 2). The two most abundant species were *G. holbrooki* and *P. olorum*, which collectively accounted for 94.8% of the total number of individuals caught (78.6% and 16.2%, respectively). The remaining 5.2% of the fish caught included the native species *G. occidentalis* (2.2%) and *L. wallacei* (1.8%) as well as several other native and non-native species, each of which contributed <1% (Table 2). Four native species, whose reported distribution included the study area, were absent from samples in the current study i.e. *T. bostocki, N. balstoni, G. munda* and *A. suppositus*.

A total of seven non-native species were detected during the current survey (Table 2), including one species not previously recorded from the SCP i.e. *Xiphophorus hellerii* Heckel, 1848.

Relationships between fish assemblages and abiotic characteristics

ANOSIM determined that no significant differences existed in the abiotic characteristics of the wetlands among those that contained native, non-native or mixed assemblages. However, when only those wetlands that contained mixed assemblages were analysed separately, significant differences in the abiotic characteristics were detected between those that were dominated by natives compared to those dominated by non-native species, however, the differences were small (R=0.151, P=0.001). SIMPER determined that those differences were primarily due to salinity, which was greater in the wetlands dominated by native fishes and lower in the wetlands dominated by non-native fishes. Since the two most common species were *P. olorum* (native) and *G. holbrooki* (non-native), it can be inferred that these two species are largely responsible for the native vs non-native trends identified by the above analysis.

BioEnv determined that there was a significant relationship between the environmental characteristics of

Table 2 The total number of individuals caught (N), the percentage contribution to the total number of individuals (%) and the number of water bodies in which they were encountered (Freq) for each of the six native and seven non-native fishes found during the survey of the freshwater wetlands of the southern Swan Coastal Plain.

Species	Common name	N	%	Freq
Pseudogobius olorum	Swan River Goby	10,052	16.2	32
Galaxias occidentalis	Western Minnow	1,365	2.2	23
Leptatherina wallacei	Western Hardyhead	1,111	1.8	4
Nannoperca vittata	Western Pygmy Perch	334	<1	10
Bostockia porosa	Nightfish	57	<1	8
Galaxiella nigrostriata	Black-Stripe Minnow	1	<1	1
Gambusia holbrooki	Eastern Gambusia	48,890	78.6	71
Tandanus tandanus	Freshwater Catfish	175	<1	1
Leiopotherapon unicolor	Spangled Perch	117	<1	1
Carassius auratus	Goldfish	62	<1	10
Puntius conchonius	Rosy Barb	58	<1	2
Xiphophorus hellerii	Swordtail	1	<1	1
Geophagus brasiliensis	Pearl Cichlid	1	<1	1

the wetlands and the composition of fish assemblages, but that the correlation was low. The greatest, significant correlation for the rank similarity of wetlands between abiotic characteristics and the fish datasets was for a combination of salinity, water depth and vegetation score (ρ=0.279; P=0.01).

When the abundances of the *P. olorum* and *G. holbrooki* were examined in relation to wetland salinities in more detail it was determined that six of the seven highest abundances of *P. olorum* occurred in wetlands with salinity greater than 1‰. Conversely, 11 of the 12 highest abundances of *G. holbrooki* occurred below this same salinity threshold. Catches of *G. holbrooki* averaged only 26 individuals.net^{-1} in wetlands with a salinity greater than 1‰, whereas below that salinity, the average catch was 270 individuals.net^{-1}, and the maximum recorded was 5000 individuals.net^{-1}.

Only 10 of the surveyed wetlands contained *N. vittata* of which all had scores for vegetation greater than 3. Furthermore, the largest numbers of this fish were found in wetlands with vegetation scores of 5 or 6.

DISCUSSION

This study highlights that many of the wetland habitats on the SCP identified as perennial no longer hold permanent water, and that in those remaining wetlands non-native fish outnumber native fish considerably. It follows then, that the native fish populations in the wetlands of the SCP are under considerable pressure from both habitat loss and interactions with non-native fish species. The number of perennial wetlands that are capable of supporting fish is much smaller than historically recorded and native fish in this region are far less numerous and less widely distributed than non-native species. Also, a number of species previously reported from the region were not found during this study. The wide distribution of non-native fish in the wetlands of the SCP indicates that the non-contiguous nature of these water bodies has not presented a significant barrier to the spread of non-native fishes.

Although the primary focus of the project was to survey the fish faunas of the perennial wetlands of the SCP, it included by necessity, determination of which water bodies that were previously recorded as perennial continued to be so. The results from this study indicate that many of the perennial wetlands recorded by the Geomorphic Wetlands Swan Coastal Plain dataset did not hold permanent water during the survey period. This obviously has significant ramifications for the fishes of the region. As previously noted, the wetlands of the SCP are subject to drying as a result of several pressures including a general climatic drying trend, groundwater abstraction and active drainage (Davis & Froend 1999). On top of these factors, the year preceding the survey was both considerably hotter and drier than the annual averages for the region.

It is acknowledged that additional habitats other than enclosed wetlands exist for freshwater fish on the SCP, including artificial impoundments, rivers and streams (e.g. Morgan *et al.* 1998, 2004, 2006; Morgan & Beatty 2008). While these water bodies have been reported to contain populations of native fishes, more surveys are required to update contemporary distributions. While these other environments may act as refuges for remnant populations across the study area, these water bodies are also susceptible to the drying trend affecting the wetlands of the region. Likewise, while substantial populations of native fishes are located in the southern regions of south-western Australia, particularly in wilderness areas, the loss and degradation of habitat in the urbanised Perth metropolitan area and more generally the SCP, represents a significant loss for native fish biodiversity through range contraction and fragmentation, with a likely decrease of genetic diversity.

Non-native fishes are more widely spread in the wetlands of the SCP and outnumber native fishes overall by four to one (relative survey abundance). *Puntius conchonius* has previously been reported on the SCP (Duffy *et al*. 2013) as well as further south (Beatty *et al*. 2006) and was found at two locations during this survey. *Xiphophorus hellerii* has been found to the north of the SCP (Morgan & Gill 2001) and was only found once on the SCP during this survey. *Tandanus tandanus* was recorded in water bodies of Western Australia by Duffy *et al*. (2013) and was present in only one water body.

Despite the prevalence of non-native fishes, the patterns of abundance of both native and non-native species indicate that some native fishes have a degree of resilience to the presence of non-native fish. Analysis of the assemblage composition of the fish faunas indicates that native fish populations have similar, or greater, relative abundances when they co-occur with non-native species as they do in native-only wetlands. This is not the case for non-native species, which are in much lower abundances when they co-occur with native species than in non-native-only wetlands. One possible cause for these patterns of abundance, which is somewhat supported by analysis of environmental characteristics, is that the salinity of the wetlands, coupled with the differing responses to salinity of the two most abundant species (*G. holbrooki* and *P. olorum*) creates a threshold that mediates their competitive success, i.e. in many wetlands with lower salinity, *G. holbrooki* are able to proliferate to the exclusion of native species. However in wetlands with slightly elevated salinity *P. olorum* is able to maintain a competitive advantage over *G. holbrooki*. The concept that salinity may mediate non-native vs native interactions is supported by the results of other studies. Alcaraz *et al.* (2008) examined changes in the interactions between *G. holbrooki* and the Mediterranean Killifish, *Aphanius fasciatus* (Valenciennes, 1821) at different salinities, demonstrating that at higher salinities *G. holbrooki* became less efficient predators and were less antagonistic toward co-habiting fish, while the other species was not similarly affected. It is not suggested that *G. holbrooki* is intolerant of higher salinities, as records of survival in saline water are available (Pyke 2005), instead that the competitive advantage that allows this introduced species to proliferate is somewhat diminished.

Further evidence that native species can effectively compete with non-native species is that a population of *N. vittata* in Mason's Lake on the SCP was present, and that individuals were reproducing, and apparently in good physical condition despite being outnumbered by *G. holbrooki* at a ratio of 30:1 (Major 2009). Just prior to the sampling for that study the lake had been intensively trapped and *G. holbrooki* removed to reduce their relative abundance from 156:1 to 30:1 (Unpublished data, Department of Fisheries). It has been postulated that the reason for this and similar instances of successful native/ non-native cohabitation is the presence of dense riparian vegetation providing increased habitat complexity (Hambleton *et al.* 1996; Gill *et al.* 1999; Morgan *et al.* 2004; King & Warburton 2007; Major 2009). Our results support this assertion, since all of the wetlands in which *N. vittata* occurred in a mixed assemblage with non-native fish had moderate to high scores for vegetation cover. Furthermore, the largest populations of this species occurred in wetlands with high vegetation scores, and wetlands with low vegetation scores never contained this species. Given the high likelihood of native and non-native fishes co-occurring, the importance of maintaining or augmenting intact riparian and aquatic vegetation for any conservation and remediation actions should not be underestimated.

Four species previously reported from the SCP (Morgan *et al.* 2011) were not collected during the present survey of perennial wetlands, *i.e. T. bostocki, A. suppositus, N. balstoni* and *G. munda*. The first two species, *T. bostocki* and *A. suppositus* that were absent from samples are typically, but not exclusively, associated with lotic rather than lentic systems, with the latter species additionally occurring in estuaries (Neira *et al.* 1998; Morgan & Beatty 2008, Morgan *et al.* 2011). It is not surprising then that these species were not found, since those former environments were not the targets of this study.

Nannatherina balstoni and *G. munda* have only been recorded sporadically on the SCP, with records indicating their current core distribution is further south (Morgan *et al.* 2011). The only record of *G. munda* on the SCP is a relict population in the Ellen Brook and Lennard Brook region, and a recent report states that this population is still present, despite being well outside this species' common range, isolated, and in the same area as a considerable non-native fish incursion (Beatty *et al.* 2010). Ongoing surveys are required to determine if any other relict populations exist or if this species is otherwise absent north of Perth. Similarly, *N. balstoni* was most recently recorded from isolated populations on the SCP near the Moore River, north of Perth (Morgan *et al.* 1998), but has not been formally documented in this area since that time (Department of the Environment, World Heritage and the Arts, 2008). It is likely that this species' range has now contracted to the south.

Only a single individual of *G. nigrostriata* was encountered during this study, however this is probably a reflection of its typical habitat, ephemeral wetlands, not being the target of this study as well as its mainly southern distribution. The single location at which it was found during this study (Chandala Nature Reserve) is the same site as reported by McLure & Horwitz (2009). The other two SCP remnant populations documented by Galeotti *et al.* (2010) were not re-surveyed as they were dry at the time they were visited. This suggests that to accurately capture the distribution of *G. nigrostriata*, future sampling designs should accommodate ephemeral wetlands when they contain water. Regardless of whether *G. nigrostriata* only temporarily inhabits ephemeral wetlands and populations retreat to refuge wetlands containing permanent water during the dry months, or is able to aestivate and remain in the ephemeral wetlands, it is critical for the continued survival of this species to find and protect the wetlands in which it resides. This is equally applicable to the SCP locations as it is throughout its more southern range.

The dual pressures of habitat loss through wetland drying, and the incursion of non-native fishes appear to have drastically reduced the number of wetlands that are currently inhabited by native freshwater fishes on the southern SCP. Less than 10% of the water bodies surveyed contained only native fish, with an even smaller proportion containing only obligate freshwater species endemic to the region such as *N. vittata, G. occidentalis, G. nigrostriata* and *B. porosa* (seven wetlands, Figure 2b). These few wetlands should be highlighted as priorities for habitat conservation and receive attention for further management actions. Further study is recommended to adequately inform ongoing management. In particular, a greater spatial coverage is recommended, with the survey of fish in additional inland and northern wetlands of the Southwestern Province, and the inclusion of ephemeral water bodies to more accurately gauge the distribution of *G. nigrostriata*. Additionally, a study of the genetic stock structure of the native fishes in these wetlands will greatly inform potential management strategies such as restocking and supplementation programs as part of broader conservation efforts.

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REFERENCES

Australian Bureau of Statistics 2012. *Australian Bureau of Statistics.* <http://www.abs.gov.au/websitedbs/D3310114.nsf/home/Home?opendocument>. (Accessed 3 October 2012).

Alcaraz C, Bisazza A & Garcia-Berthou E 2008. Salinity mediates the competitive interactions between invasive mosquitofish and an endangered fish. *Oecologia* **155**, 205–213.

Allen G R, Midgley, S H & Allen M 2002. *Field guide to the freshwater fishes of Australia.* Western Australian Museum.

Balla S A 1994. *Wetlands of the Swan coastal plain: Volume 1: Their nature and management.* Water Authority of Western Australia.

Balla S A & Davis J A 1993. *Wetlands of the Swan coastal plain: Volume 5: Managing Perth's wetlands to conserve the aquatic fauna.* Water Authority of Western Australia.

Beatty S J, Morgan D L, Klunzinger M W & Lymbery A J 2010. *Aquatic macrofauna of Ellen Brook and the Brockman River: fresh water refuges in a salinised catchment.* Murdoch University. Centre for Fish & Fisheries Research, Western Australia.

Beatty S J, Morgan D L, Jury C & Mitchell J 2006. *Fish and freshwater crayfish in streams in the Cape Naturaliste region and Wilyabrup Brook*. Centre for Fish & Fisheries Research, Murdoch University Report to the Cape to Capes Catchment Group and GeoCatch.

Beatty S J, Morgan D L, Rashnavadi M & Lymbery A J 2011. Salinity tolerances of endemic freshwater fishes of south-western Australia: Implications for conservation in a biodiversity hotspot. *Marine and Freshwater Research* **62**, 91–100.

Beatty S J & Morgan D L 2013. Introduced freshwater fishes in a global endemic hotspot and implications of habitat and climatic changes. *Bioinvasions Records* **2**, 1–9.

Bekle H & Gentilli J 1993. History of the Perth lakes. *Journal and Proceedings of the Royal Western Australian Historical Society (Inc.)* **10**, 443–460.

Bureau of Meteorology 2010. *Annual climate summary for Perth: Second warmest year on record for Perth*. <http://www.bom.gov.au/climate/current/annual/wa/archive/2009.perth.shtml>. (Accessed 20 October 2014).

Brearley A 2005. *Ernest Hodgkin's Swanland: estuaries and coastal lagoons of south-western Australia.* University of Western Australia Press. Crawley, Western Australia.

Clarke K R & Gorley R N 2006. *User manual/Tutorial.* PRIMER – E Ltd. Plymouth, United Kingdom.

CSIRO 2009. *Surface water yields in south-west Western Australia. A report to the Australian Government from the CSIRO south-west Western Australia Sustainable Yields Project.* CSIRO Water for a Healthy Country Flagship, Australia. <http://www.clw.csiro.au/publications/waterforahealthycountry/swsy/pdf/SWSY-Main-Report-SurfaceWater.pdf>. (Accessed 20 October 2014).

Cummings B & Hardy A 2000. *Revision of the Interim Biogeographic Regionalisation for Australia (IBRA) and development of Version 5.1 – Summary report.* <http://web.archive.org/web/20060905215218/http://www.deh.gov.au/parks/nrs/ibra/version5-1/summary-report/index.html>. (Accessed 15 December 2014).

Davis J A & Froend R 1999. Loss and degradation of wetlands in South-western Australia: underlying causes, consequences and solutions. *Wetlands Ecology and Management* **7**, 13–23.

Davis J, Rosich R S, Bradley J S, Growns J E, Schmidt L G & Cheal F 1993. *Wetlands of the Swan coastal plain: Volume 6. Wetland classification on the basis of water quality and invertebrate community data.* Water Authority of Western Australia, Perth, Australia.

Department of the Environment, World Heritage and the Arts 2008. *Approved conservation advice for* Nannatherina balstoni *(Balston's Pygmy Perch) Threatened Species Scientific Committee.* <http://www.environment.gov.au/biodiversity/threatened/species/pubs/66698-conservation-advice.pdf>. (Accessed 23 June 2011).

Department of Environment and Conservation 2011. *Geomorphic wetlands Swan Coastal Plain dataset.* <www.dec.wa.gov.au/content/view/5317/1556/>. (Accessed 21 June 2011).

Department of Fisheries 2012. *Freshwater fish distribution in Western Australia.* <http://freshwater.fish.wa.gov.au/default.aspx>. (Accessed 18 June 2014).

Duffy R, Snow M & Bird C 2013. The convict cichlid *Amatitlania nigrofasciata* (Cichlidae): first record of this non-native species in Western Australian waterbodies. *Records of the Western Australian Museum* **28**, 7–12.

Fairhurst E 1993. *The feeding ecology of freshwater fishes in wetlands of the Swan Coastal Plain.* Honours thesis. Murdoch University, Perth Western Australia.

Galeotti D M, McCullough C D & Lund M A 2010. Black-stripe minnow *Galaxiella nigrostriata* (Shipway 1953) (Pisces: Galaxiidae), a review and discussion. *Journal of the Royal Society of Western Australia* **93**, 13–20.

Gill H S, Hambleton S J & Morgan D L 1999. Is the mosquitofish *Gambusia holbrooki* (Poeciliidae), a major threat to the native freshwater fishes of South-western Australia? In: *Proceedings of 5th Indo-Pacific Fish Conference, 3 – 8 November 1997, Noumea, New Caledonia*.

Havel J J 1975. The effects of water supply for the city of Perth, Western Australia, on other forms of land use. *Landscape Planning* **2**, 75–132.

Hambleton S J, Gill H S, Morgan D L & Potter I C 1996. *Interaction of the introduced mosquitofish (Gambusia holbrooki) with native fish species at the Capel Wetlands Centre.* Capel Wetlands Centre technical report No. 33.

Keighery B 1991. *A guide to plant community survey for the community. Bushland plant survey.* Wildflower Society of W.A. (Inc.) Perth.

King S & Warburton K 2007. The environmental preferences of three species of Australian freshwater fish in relation to the effects of riparian degradation. *Environmental Biology of Fishes* **78**, 307–316.

McLure N & Horwitz P 2009. *An investigation of aquatic macroinvertebrate occurrence and water quality at Lake Chandala, Western Australia.* Unpublished report to Department of Environment and Conservation, Western Australia.

Major J 2009. *Native fish fauna in Perth wetlands are declining with increasing wetland degradation.* Honours thesis. University of Western Australia.

Morgan D L & Beatty S J 2008. Fishes and freshwater crayfishes of major catchments of the Leschenault Estuary: Preston and Brunswick River, including first record of a freshwater gudgeon (Eleotridae) from south-western Australia. *Journal of the Royal Society of Western Australia* **91**, 155-161.

Morgan D L & Gill H S 2000. Fish associations within the different inland habitats of lower south-western Australia. *Records of the Western Australian Museum* **20**, 31–37.

Morgan D L & Gill H S 2001. The green swordtail *Xiphophorus helleri* Heckel (Poeciliidae): another aquarium fish established in the wild in Western Australia. *Records of the Western Australian Museum* **20**, 349–352.

Morgan D L, Gill H S & Potter I C 1995. Life cycle, growth and diet of Balston's pygmy perch in its natural habitat of acidic pools. *Journal of Fish Biology* **47**, 808–825.

Morgan D L, Gill H S & Potter I C 1998. Distribution, identification and biology of freshwater fishes in south-western Australia. *Records of the Western Australian Museum* Supplement No. 56.

Morgan D L, Gill H S, Maddern M G & Beatty S J 2004. Distribution and impacts of introduced freshwater fishes in Western Australia. *New Zealand Journal of Marine and Freshwater Research* **38**, 511–523.

Morgan D L, Chapman A, Beatty S J & Gill H S 2006. Distribution of the spotted minnow (*Galaxias maculatus* (Jenyns, 1842)) (Teleostei: Galaxiidae) in Western Australia including range extensions and sympatric species. *Records of the Western Australian Museum* **23**, 7–11.

Morgan D L, Beatty S J, Klunzinger M W, Allen M G & Burnham Q F 2011. *Freshwater fishes, crayfishes and mussels of south-western Australia*. SERCUL & Murdoch University.

Neira F J, Miskiewicz A G & Trnski T 1998. *Larvae of Temperate Australian Fishes: Laboratory guide for larval fish identification*. University of Western Australia Press, Nedlands Western Australia. 474pp.

Pyke G H 2005. A review of the biology of *Gambusia affinis* and *G. holbrooki*. *Reviews in Fish Biology and Fisheries* **15**, 339–365.

Smith K D, Pen L J & Knott B 2002a. Genetic and morphological study of the Black-stripe minnow, *Galaxiella nigrostriata* (Salmoniformes : Galaxiidae), including a disjunct population near Perth, Western Australia. *Records of the Western Australian Museum* **21**, 285–290.

Smith K D, Knott B & Jasinska E J 2002b. Biology of the Black-stripe minnow *Galaxiella nigrostriata*, (Galaxiidae) in an acidic, black-water lake in Melaleuca Park near Perth, Western Australia. *Records of the Western Australian Museum* **21**, 277–284.