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Historical abundance and distribution of the native flat oyster (*Ostrea angasi*) in estuaries of the Great Southern region of Western Australia help to prioritise potential sites for contemporary oyster reef restoration

P. A. Cook[A,D], *B. Warnock*[A], *C. L. Gillies*[B,C] *and A. B. Hams*[B]

[A]Centre of Natural Resource Management, The University of Western Australia, Albany, WA 6330, Australia.
[B]The Nature Conservancy, Carlton, Vic. 3053, Australia.
[C]TropWATER, Centre for Tropical Water and Aquatic Ecosystem Research, James Cook University, Townsville, Qld 4811, Australia.
[D]Corresponding author. Email: peter.cook@uwa.edu.au

Abstract. Reefs of the flat oyster (*Ostrea angasi*) were once common along the southern coasts of Australia. Historical and current literature relating to *O. angasi* was used to identify bays and estuaries where this species once existed. In many estuaries of Western Australia, current populations are significantly lower than historical levels, including in Princess Royal Harbour and Oyster Harbour, near Albany. The main causes of the declines included overfishing, combined with the use of destructive fishing methods, such as dredging. Other factors, such as sedimentation, increased nutrient input and loss of seagrass, may have contributed to the loss of oyster reefs, and may have inhibited effective recovery. The possible impact of the protozoan pathogen *Bonamia exitiosa* is uncertain, although it is known to have severely affected flat oyster populations in other parts of the world. The fact that *O. angasi* reefs in Oyster Harbour did not recover after the fishery ceased suggests that restoration activities, aimed at restarting the ecosystem services that the oyster reefs once provided, should be undertaken. This paper suggests that the historical presence of *O. angasi* could be an effective starting point for prioritising potential restoration sites and details the prioritisation protocol that was used in recent restoration activities.

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Introduction

Worldwide, shellfish reefs underpin a range of ecosystem services, including water filtration, nutrient cycling and the provision of invertebrate and fish habitat (Breitburg and Miller 1998; Coen *et al.* 1999; Dealteris *et al.* 2004; Newell and Koch 2004; Newell *et al.* 2005; Tang *et al.* 2011; Grabowski *et al.* 2012). However, shellfish reefs have declined in many parts of the world (Lotze *et al.* 2006; Beck *et al.* 2011; zu Ermgassen *et al.* 2013; Warnock and Cook 2015; Gillies *et al.* 2020). In some cases, reef losses have exceeded 90% compared with historical abundance. Several different factors may have contributed to such declines, the most common of which is overfishing, particularly where fishing is undertaken using destructive fishing methods (e.g. dredging) that damage or remove hard substrate (Kirby 2004; Lenihan and Peterson 2004; Lotze *et al.* 2006; Beck *et al.* 2011). Other factors, such as disease, excessive nutrient input and sedimentation, compound this initial decline and may reduce or prevent the natural recovery of oyster beds (Lenihan and Peterson 1998; Lenihan *et al.* 1999; Kirby 2004; Mann and Powell 2007; Ogburn *et al.* 2007; Beck *et al.* 2011; Diggles 2013).

Reefs of the flat oyster (*Ostrea angasi*) were once common in many estuaries along the southern coastline of Australia but were mostly lost between *c.* 1840 and 1870. Few intact oyster beds remained by the end of the 19th century (Nell 2001; Hamer *et al.* 2013; Alleway and Connell 2015; Gillies *et al.* 2018). Similar losses have been noted in South Australia and Victoria (Nell 2001; Hamer *et al.* 2013; Alleway and Connell 2015). This paper records the 'ecological history' of *O. angasi* in Western Australia, and comments on the timing and potential causes of the declines. The second part of the paper suggests how understanding the historic distribution of these oysters, and the causes of historic declines, may help guide ecosystem restoration efforts that are currently being undertaken in Western Australia.

Methods

Primary and secondary literature relating to *O. angasi* in Western Australia was examined to identify locations where this species once existed. Primary data sources included annual reports from the State Commissioner for Fisheries (e.g. Saville-Kent 1894) and other fisheries reports (e.g. Aldrich 1934), as well as records and actual specimens available through the West Australian Museum.

The museum collections included *O. angasi* shells for which the sampling location, the name of the collector and the collection date have been recorded. All samples were coded to record whether the animal was alive or dead at the time of collection.

Secondary information sources included newspaper articles (National Library of Australia Trove database; http://trove.nla.gov.au/) and the Albany Library Historical Collection Archives (http://history.albany.wa.gov.au/). No attempt was made to record changes in reef abundance over time because of the paucity of robust quantitative and qualitative information.

Once Oyster Harbour had been selected as a suitable location for a case study on the restoration of *O. angasi* reefs, it was then necessary to establish a protocol to prioritise the most suitable reef restoration sites within the harbour, taking a wide variety of factors into account. The development of a 'suitability model' for potential restoration sites was based on the unpublished protocols recommended by Kate Longley-Woods and Simon Reeves (The Nature Conservancy, Australia). A site selection process was conducted using geospatial information relevant to the requirements of *O. angasi*. The various competing interests of a range of stakeholders were also taken into account, including recreational users, navigational safety (markers and channels) and commercial interests, such as aquaculture leases and fishing areas. Locations supporting seagrass beds were avoided. Further details of this process are described later in the paper.

Results and discussion

Past distribution of O. angasi *in south-west Western Australia*

The distribution of *O. angasi*, as indicated from shell collections housed at the Western Australian Museum, suggests that the species is, or has been at some point, broadly distributed throughout the south-west of Western Australia (Fig. 1). However, it is possible that the presence of shells in some areas may have resulted from the movement of live oysters by humans. Samples were recorded from both estuarine environments (e.g. Oyster Harbour and Nornalup Inlet) and protected inshore waters (e.g. Cockburn Sound and Esperance; Appendix 1).

Fig. 2 shows that, in terms of samples collected by the WA Museum, most were collected during the 1970s and 1980s. These periods coincide with a Museum policy of collection enlargement at that time. The most recent collection came from Mandurah in 2003, and was identified as living at the time of capture.

Early distribution and abundance of O. angasi

Early explorers found plentiful supplies of *O. angasi* in Western Australia. There were so many oyster beds in Oyster Harbour that George Vancouver ran his vessel aground on a bank of oysters while attempting to leave the harbour in 1791 (Baudin 1809; Vancouver 1898). To commemorate the event, Vancouver named the estuary Oyster Harbour (Vancouver 1898). Baudin (1809) noted the large size of the flat oysters found in the harbour, but neither he nor Vancouver mapped the precise location of the reefs in the harbour.

A dredge fishery for oysters existed in Oyster Harbour, Princess Royal Harbour and King George Sound from the mid-1800s until *c*. 1880, forming the basis of a 'lucrative shellfish trade' (Saville-Kent 1893*a*, 1893*b*, 1894; Thompson 1897). However, Saville-Kent noted that the fishery was significantly depleted at least 15 years before his 1893 visit (Saville-Kent 1893*a*). Although Saville-Kent did not record the precise extent of the oyster beds, he suggested in 1893 (Saville-Kent 1893*b*), that 'many square miles' of oyster banks still existed in both Oyster Harbour and Princess Royal Harbour. He also suggested that, with a little effort, these beds could be resuscitated (Saville-Kent 1893*b*). The Chief Inspector of Fisheries (C. F. Gale) visited

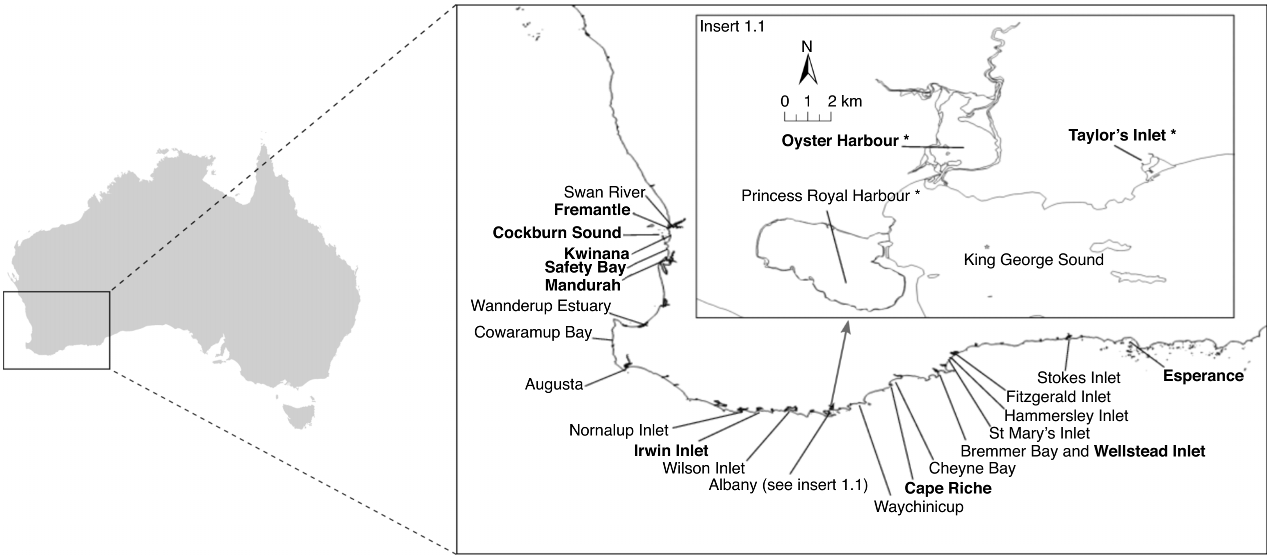

Fig. 1. Locations of oyster samples collected by the Western Australian Museum between 1919 and 2003. Locations where at least one sample was identified as probably alive at time of collection are marked in bold. Locations where commercial fisheries were known to exist are marked with an asterisk (*).

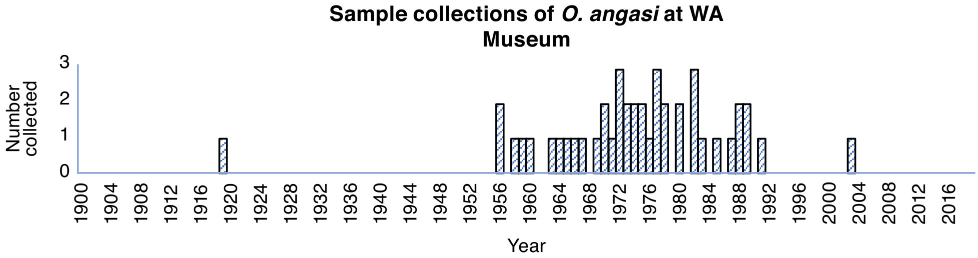

Fig. 2. Number of *O. angasi* individuals collected in any specific year by the Western Australian Museum from 1919 to 2003. The highest number of oysters was collected between 1970 and 1990.

Albany in 1899 and noted that 'small beds still exist' in the deeper waters of Oyster Harbour (Gale 1899).

In 1913, the annual report on the fisheries of the state identified Oyster Harbour as an area where *O. angasi* could still be obtained (Gale 1900, 1905; Inspector of Fisheries 1912, 1913). The state of oyster stocks in the nearby Irwin and Nornalup inlets was described in a 1934 report on Western Australian Fisheries (Aldrich 1934). Although not noted in that report, it appears that in Nornalup Inlet *O. angasi* beds were present until at least the 1920s (Linton 1923). Linton (1923) described the beds in Nornalup Inlet as 'the best oyster country of any of the inlets [in the South West]'. He suggested that depletion of the stock was unlikely because no dredging occurred in the inlet (Linton 1923). However, in what appears to be a contradictory statement, Senddan (1923) noted in a report in the *Western Mail* that although the oysters in Nornalup were 'rather too large to eat, some steps are required to preserve the oyster beds from total destruction'.

Anthropogenic impacts on O. angasi

Overfishing and a lack of appropriate management protocols have contributed to oyster population declines in South Australia, Victoria and New South Wales (Nell 2001; Hamer *et al.* 2013; Alleway and Connell 2015). An inappropriate fishing method (dredge fishing) was often used to harvest oysters, and beds were often fished to exhaustion. Another problem was that oyster shell was used in the production of lime for mortar, and this was another factor that contributed to the loss of oyster beds. In some cases, shell beds were so completely destroyed that recovery by settlement of spat was limited because hard substrate was no longer available. Similar problems contributed to the loss of oyster beds in Oyster Harbour (Warnock and Cook 2015).

Indirect impacts on O. angasi

Environmental changes that occurred in both Princess Royal Harbour and Oyster Harbour may have further inhibited the recovery of oyster beds. For example, land clearing in the Oyster Harbour catchment that occurred in the 1950s and 1960s increased sedimentation rates in the King and Kalgan rivers, as well as in Oyster Harbour (Hodgkin and Clark 1990*a*), that may have smothered benthic habitats, such as oyster beds and seagrass meadows.

Recent studies of oyster distribution

A recent study in Nornalup and Wilson inlets near Albany did not find any live individuals, but *O. angasi* shells were abundant in some locations (Western Australian Department of Environment and Conservation and Western Australian Marine Parks and Reserves Authority 2009). Similarly, no live specimens were found in any south-west estuaries during routine sampling in the 1980s and 1990s (Hodgkin and Clark 1988, 1989*a*, 1989*b*, 1990*a*, 1990*b*, 1999). However, these studies were not specifically aimed to sample *O. angasi*. Therefore, it is possible that remnant populations may have been missed.

In 2002, 10 flat oysters were collected from Oyster Harbour and their mitochondrial DNA was typed for *16S* and cytochrome oxidase 1 (*CO1*). Seven of the collected oysters were identified as *O. angasi*, whereas three were identified as *Ostrea edulis* (Morton *et al*. 2003).

Restoration attempts using aquaculture

In 1893, Saville-Kent (Commissioner of Fisheries for Western Australia) attempted to rebuild the oyster stocks in Princess Royal Harbour in order to 'resuscitate' the fishery. He suggested that spat settled regularly on moored vessels and other solid substrates in the harbour, but that there was insufficient hard substrate to develop large populations (Saville-Kent 1893*b*). He identified a small waterway that was open to the sea via a culvert as a location to establish a population of *O. angasi*. Live brood stock oysters were collected and placed on wooden frames with wire netting mesh, or on wooden planks attached to bricks. By May 1895, the oysters appeared to be doing well but, by October 1896, the waterway had filled with silt and seaweed (Learoyd 1896), smothering the oysters and facilitating the growth of mud worms. Learoyd (1896) suggested that by October 1896, very few *O. angasi* were still alive and all were infested with the mud worm. Oyster Harbour was then suggested as a better location to develop oyster beds, and a different species of oyster, *Saccostrea glomerata*, was recommended by Learoyd (1896).

Further attempts to culture *O. angasi* in hatcheries did not occur until the 1990s. A local company, Ocean Foods International Pty Ltd (OFI), secured leases in both Oyster Harbour and King George Sound and developed a local hatchery. However, it soon became apparent that the local *Ostrea* spp. was susceptible to the protozoan parasite *Bonamia exitiosa*, which is lethal to many oyster species (Dinamani *et al.* 1987; Hine and Jones 1994; Adlard 2000; Cranfield *et al.* 2005). Following a high level of mortality, OFI began producing an alternative oyster species, namely *Saccostrea glomerata*, which was less affected by the *Bonamia* parasite

Table 1. Parameters considered in preparing suitability scores for oyster reef restoration sites in Oyster Harbour
DO, dissolved oxygen; MPA, marine protected area

Parameter	Envelope	Criteria (more suitable = 4; less suitable = 0)	Rational and notes
Bathymetry	0–12 m	2–9 m = 4; 0–2 m = 3; >9 m = 0	Logistically difficult to construct <10 m; risk of disturbance in depths <3 m
Salinity average	25–37 ppt	35–30 = 4; 30–25 = 3; <25 = 0	Not included in model, all areas within known ecological tolerance
Temperature maximum	8–29°C	8–24°C = 4; 24–28°C = 2; >28°C = 0	Not included in model, all areas within known ecological tolerance
DO minimum	>4 mg L^{-1}	>4 mg L^{-1} = 4; <4 mg L^{-1} = 0	Not included in model, all areas within known ecological tolerance
Substrate	Sand, soft sediment or unconsolidated shell–sand matrix	Sand or soft sediment = 4; all other areas = 0	Not included in model due to suitable, soft substrate across study area
Seagrass avoidance	+5-m buffer from areas >20% coverage	Areas outside = 4; known patches = 0	Avoided impacts to existing seagrass beds
Seagrass proximity	5–500 m	Areas within 5- to 500-m buffer = 4; all other areas = 2	Seascape connectivity
Rocky reef proximity	5–500 m	Areas within 5- to 500-m buffer = 4; all other areas = 2	Not included in model, absent from location
Shipping channel avoidance			
Small craft channels	+50-m buffer	Areas within buffer = 0; all other areas = 4	Reduce threat of collision, navigation hazard
Large craft channels	+250-m buffer	Areas within buffer = 0; all other areas = 4	Not included in model, absent from location
Recreation, ski or watercraft zones avoidance	+250-m buffer	Areas within buffer = 0; all other areas = 4	Reduce threat of collision, navigation hazard
Aquaculture zones avoidance	+500-m buffer	Areas within buffer = 0; all other areas = 4	Safe working zone from aquaculture sites
Commercial fishing zones avoidance	+250-m buffer	Areas within buffer = 0; all other areas = 4	Avoided impact on fishing gear
MPAs	+500-m buffer	Areas within buffer = 0; all other areas = 4	Not included in model, absent from location
Avoidance of culturally sensitive areas	+250-m buffer	Areas within buffer = 0; all other areas = 4	Not included in model, entire location is a study-registered cultural site
Proximity of historical reefs	Within 250 m	Within 250 m = 4; all other areas = 2	Not included in model, entire study area is known to contain historical reefs
Proximity of remnant reefs or known areas with a high density of oysters	Within 250 m	Within 250 m = 4; all other areas = 2	Not included in model, no known areas in study area
Distance from shore	Within 2 km	All areas within 2 km = 4, clip out all other areas	Not included in model, all areas within 2 km of shore

Current Oyster Reef restoration in south-west Western Australia

Once all the historical data on the previous distribution of *O. angasi* in the estuaries of south-west Western Australia had been examined, they were used to indicate the most suitable locations to restore *O. angasi* reefs. The presence of *O. angasi* shells or live oysters, either currently or in historical records, potentially indicates that, at some point in time, the waterbody where they were found was a suitable location for the species. On this basis, Oyster Harbour was selected as a suitable location for a case study on the restoration of *O. angasi* reefs. Following this, it was then necessary to establish a protocol to prioritise the most

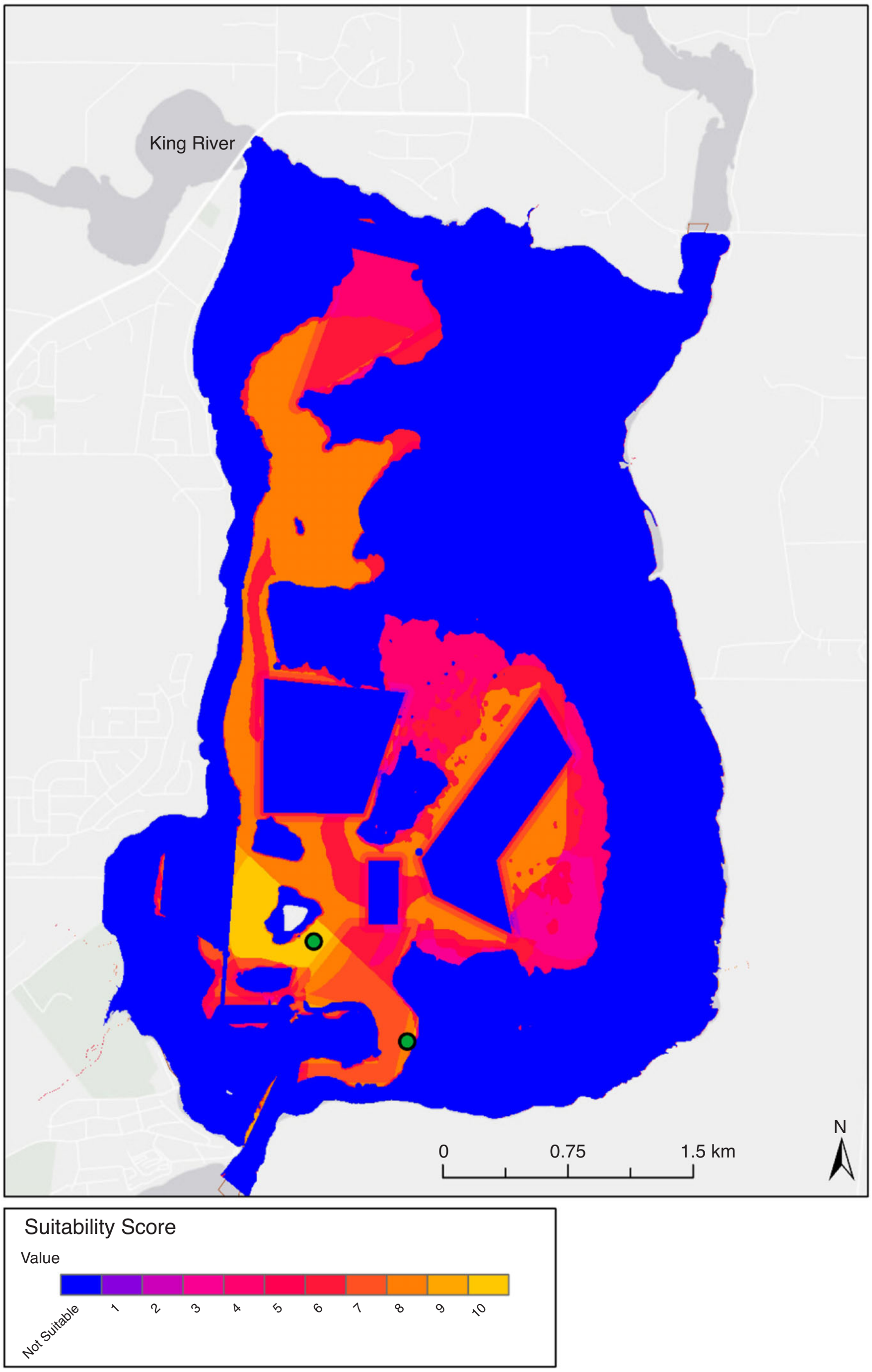

Fig. 3. Map showing suitability scores for oyster reef restoration in Oyster Harbour. The green dots represent the positions of the newly constructed restoration sites.

suitable reef restoration sites within the harbour, taking a wide variety of factors, and stakeholder views, into account. This prioritisation process is described below.

Informing restoration: a case study in Oyster Harbour

To optimise the success of the new reefs, a site selection process was conducted using geospatial information relevant to the requirements of *O. angasi*, and taking into account the various competing interests of a range of stakeholders. An assessment was undertaken comparing tolerance levels of *O. angasi* with local water quality data (salinity, temperature and dissolved oxygen concentration) collected by the Department of Water and Environmental Regulation (DWER) in Oyster Harbour (https://estuaries.dwer.wa.gov.au). Other environmental and social factors, such as seagrass habitat and alternative water usage, again accessed from DWER, were then overlayed onto the resulting maps. Scores were assigned to each parameter and an overall 'suitability score' calculated for each location. The parameters used in this process are listed in Table 1. Although all parameters outlined in Table 1 were considered, only those that were relevant for the suitability model (i.e. as indicated in rationale and notes) were included. Areas that achieved a zero score were considered unsuitable for oyster reef restoration, whereas areas with the highest scores were given the highest prioritisation for reef deployment. The resulting priority area map is shown in Fig. 3. Buffers were designed to surround areas considered not suitable (e.g. aquaculture leases and navigation channels). The maps produced from this process were used to gauge community acceptability of reef construction within the highest-priority zones.

Following this process, the most suitable areas to reconstruct *O. angasi* reefs were chosen and restoration efforts commenced. In late 2019, The Nature Conservancy constructed ~1650 m^2 of reef from 1000 tonnes (Mg) of small limestone boulders. Shortly after, ~1 million *O. angasi* spat, reared in the Albany Shellfish Hatchery, were seeded onto the reef in an effort to restore a sustainable oyster population in Oyster Harbour. Although it is still too early to accurately assess success, initial results suggest that the newly constructed reefs are on an ecological trajectory consistent with becoming fully functioning shellfish reefs in the future.

In terms of future restoration efforts within Oyster Harbour, the same site suitability maps could be used and a similar process could be followed in other bays and estuaries in Western Australia where future oyster reef restoration may be considered.

Conclusions

The lack of sufficient robust information on *O. angasi* distribution throughout the south-west of Western Australia makes quantitative evaluation of the current status of the stock very difficult, but available information suggests that the current distribution of *O. angasi* is considerably reduced from historical levels. Overfishing appears to have caused the initial decline, with destructive fishing methods exacerbating the problem. Factors such as poor water quality, increased sedimentation and the loss of seagrass are likely to have contributed to the fact that stocks have not been able to recover naturally. This lack of natural recovery over the century that followed the effective end of the *O. angasi* fishery suggested that urgent restoration efforts were required if the ecosystem services provided by oyster reefs were to be restored. A process of site selection and prioritisation has been outlined for Oyster Harbour that used the historical presence of *O. angasi* as a starting point, and it is suggested that this approach could be used in the process of identifying and prioritising suitable restoration sites in other parts of the state.

Data availability

All data held by corresponding author and are available as required.

Conflict of interest

The authors declare that they have no conflicts of interest.

Declaration of funding

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Appendix 1. List of samples collected by the Western Australian Museum, date the sampling took place and the status of the shell at time of sampling (L, live; D, dead; ?, unknown)

The exact number of oysters collected during each sampling event is not indicated in the records

Augusta		Esperance		Kwinana		Safety Bay	
1956	D	1974	D	1982	L	1965	L
1980	D	1975	D	Mandurah		St Mary's Inlet	
Bremer Bay		1976	L	1958	?	1991	?
1970	D	1985	L	2003	L	Stokes Inlet	
1972	?	1989	D	Nornalup Inlet		1982	D
Cape Riche		Fitzgerald Inlet		1967	D	Swan River	
1992	L	1970	D	1969	D	1973	?
Cheyne Bay		Fremantle		1989	?	Wannderup Estuary	
1968	D	1919	L	Oyster Harbour		N/A	D
Cockburn Sound		Hamersley Inlet		1956	D	Waychinicup	
1964	L	1977	?	1959	?	1978	D
1972	L	Irwin Inlet		1960	L	1988	D
1973	L	1971	L	1963	L	Wellstead Inlet	
1975	L	Kalgan River		1980	L	1972	L
1977	L	1977	D	Princess Royal Harbour		Wilson Inlet	
1983	?	King George Sound		1978	?	1974	D
Cowaramup Bay		1982	D	1988	?		
1966	?	1987	D				